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Association Euratom - Risø National Laboratory for Sustainable Energy, Technical University of Denmark - Annual Progress Report 2008

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Risø-R-Report

Edited by S.B. Korsholm, P.K. Michelsen, J.J. Rasmussen and C.M. Westergaard
Risø-R-1684(EN)
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Risø DTU
National Laboratory for Sustainable Energy

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Abstract (max. 2000 char.):

The programme of the Research Unit of the Fusion Association Euratom - Risø National Laboratory for Sustainable Energy, Technical University of Denmark, covers work in fusion plasma physics and in fusion technology. The fusion plasma physics research focuses on turbulence and transport, and its interaction with the plasma equilibrium and particles. The effort includes both first principles based modelling, and experimental observations of turbulence and of fast ion dynamics by collective Thomson scattering. New activities in technology related to development of high temperature superconductors have been initiated in 2008. Minor activities are system analysis, initiative to involve Danish industry in ITER contracts and public information. A summary is presented of the results obtained in the Research Unit during 2008.

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Contents,

Preface

In 2006 seven parties, EU, Japan, Russia, China, USA, Korea and India, signed the agreement to build and exploit ITER, and to place ITER in Cadarache in France. ITER is a major experimental facility for the development of fusion as an energy source. It is expected that ITER will be ready for scientific exploitation in 2018. The mission of ITER is to demonstrate that nuclear fusion can be exploited as an energy source. ITER represents an unprecedented international cooperation in the field of science and technology. It also represents a valuable opportunity for cooperation between public research organisations and private industry. Risø DTU participates in the internationally coordinated activities to develop fusion and sees itself as having a key role in facilitating the participation of Danish industries in the international fusion programme.

The principle being pursued with ITER is the fusion of hydrogen isotopes to form helium. To make the fusion process run at a significant rate the hydrogen gas must be heated to high temperatures where it ionises and turns into a plasma. The plasma must be confined to achieve suitable densities and sustain the high temperature. ITER will use a magnetic field for the confinement. While fusion holds the promise of providing a sustainable source of energy, which is environmentally sound, it also presents considerable scientific and engineering challenges. Key issues in the final steps towards realising fusion energy production include:

Improving the plasma energy confinement, that is the ratio between the energy of the plasma and the heating power required to sustain the plasma energy. Improving energy confinement implies reducing energy transport out of the plasma, which in principal is due to turbulence. Thus, one of the key issues is to understand and control turbulence.

Channelling the energy of fast ions, produced in fusion reactions, into heating the bulk plasma without driving turbulence and without premature exit of the fast ions from the plasma requires understanding and control of the dynamics of the fast ions in interaction with other particles and with waves.

After merging with the Technical University of Denmark (DTU) in January 2007 Risø has become an institute under DTU with the new name Risø National Laboratory for Sustainable Energy, Technical University of Denmark, in short Risø DTU. As DTU covers many technical and scientific fields of interest for the development of fusion energy, the possibility for expanding the Danish activities in the field are being explored. Investigations of advanced superconductors operating in high magnetic field have now been included in the work plan 2008-2011. Other activities on neutron radiation damages and new material studies are under consideration.

The main contributions from Risø DTU to fusion research in 2008 have been: 1) Models for investigating turbulence and transport are continually improved, and benchmarked against experiments. 2) Central to understanding the dynamics of fast ions is are temporally and spatially resolved measurements of the fast ion velocity distributions in the plasma. Risø DTU, in collaboration mainly with EURATOM partners, is exploiting and developing millimetre wave based collective Thomson scattering (CTS) diagnostics at the TEXTOR and ASDEX upgrade tokamaks in FZ-Jülich and the Max-Planck Institute for plasma physics in Garching (near Munich). Of particular note this year has been the commissioning of the CTS system at ASDEX and the first fast ion measurements at ASDEX.

1 Summary of Research Unit activities

The activities in the Research Unit cover the main areas:

Fusion Plasma Physics, which includes:

- *Theoretical and numerical turbulence studies*. Turbulence and the associated anomalous transport of particles, energy and momentum is investigated using first principles based models and solving these by means of numerical codes in full toroidal geometry. These models are continuously being developed and benchmarked against experimental data and codes at other associations. The activities mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas.

- *Fast Ion Collective Thomson Scattering.* Risø has taken the lead in the development and exploitation of fast ion collective Thomson scattering diagnostics for TEXTOR, ASDEX Upgrade (AUG) and ITER. These projects are carried out in close collaborations with the TEC† and AUG teams.

Other activities in 2008 have been:

- Investigations of high temperature superconductors for fusion reactors have been initiated with special emphasis on the characterization of various high temperature superconductor materials

- Participation in the EFDA programme on developing a multi-region global long term energy modelling framework called EFDA-TIMES

- Activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER

- Activities on public information about fusion energy. This includes development and presentation of the "Danish Fusion and Plasma Road Show"

The **global indicators** for the Research Unit in 2008 are:

Professional staff:	12.4	man-years
Support staff:	2.6	man-years
Total expenditure - incl. mobility:	2.20	Mio Euro
Total Euratom support:	0.51	Mio Euro

† TEC: the Trilateral Euregio Cluster, a collaboration of FOM Institute for Plasma Physics, Holland; ERM/KMS, Belgium and Forschungszentrum Jülich, Germany.

2 Plasma Physics and Technology

2.1 Introduction

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A plasma is a dense collection of free ions and electrons. The transitions from solids to fluids to gases are associated with increases in internal energy, the breaking of bonds and changes of physical properties. The same is true of the transition from a gas to a plasma. The plasma is rightfully described as the fourth state of matter, its physics differing as much from that of gases as that of solids does. Just as solid state physics is involved in a broad range of applications, so it should be no surprise that plasmas have a wide range of applications, that their physics and chemistries are rich, and that the methods of generation and diagnosis are wide and complex.

Our activities in high temperature plasmas, aimed at developing fusion energy, are coordinated with the European EURATOM fusion programme through an agreement of association on equal footing with other fusion laboratories in Europe. Our EURATOM association facilitates extensive collaboration with other fusion research laboratories in Europe, crucial in the ongoing build-up of competencies at Risø DTU, and gives us access to placing our experimental equipment on large fusion facilities at the Max-Planck Institute for Plasma Physics in Garching and at the Research Centre Jülich, both in Germany. Our association with EURATOM also provides the basis for our participation in the exploitation of the European fusion research centre, JET, located in England. With its organisation of national programmes as EURATOM associations, the European fusion programme is a successful example of a large *European Research Area*. Our activities in high temperature plasma research and the development of fusion energy are introduced in subsection 2.1.1, and described in further detail in subsection 2.2 discussing turbulence and transport in fusion plasmas, and in subsection 2.3 discussing our use of millimetre waves for investigating the dynamics of fast ions in fusion plasmas.

2.1.1 Fusion plasma physics

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Producing significant amounts of fusion energy requires a plasma with a temperature of 100 to 200 million degrees and densities of 1 to 2 times 10^{20} particles per cubic metre, corresponding to a pressure of 1 to 5 atmosphere. Unlike gases, plasmas can be confined and compressed by magnetic fields. At the required temperatures the plasma must be lifted off material walls to prevent the plasma from rapid cooling. This is done by suspending the plasma in a toroidally shaped magnetic field that also acts to balance the plasma pressure. The required temperature and densities have been achieved in the joint European fusion experiment, JET. The production of net energy adds the requirement that the energy in the plasma be confined at least on the order of six seconds. The confinement time is the characteristic time for cooling off if heating was switched off or, equivalently, the ratio of plasma energy to required heating power to sustain that energy content. Achieved confinement times are on the order of one second. Higher density could compensate shorter confinement time and vice versa, so a simplified statement of the target is that the product of temperature, density and confinement time should be six atmosphere × seconds and is currently one atmosphere × seconds. Progress towards the goal principally involves improving the confinement time or, equivalently, reducing the energy transport in the plasma. The energy transport in fusion grade plasmas is principally due to turbulence, one of our main research activities reported in subsection 2.2. Significant progress towards the goal is expected with the next step fusion experiment, ITER. In ITER significant fusion rates are expected and with that the fast ion populations in the plasma will increase dramatically compared with present machines. The fast ions may then influence the plasma significantly. As a consequence, the dynamics of fast ions and their interaction with the rest of the plasma is one of the central physics issues to be studied in ITER. It is in fact also one of our main research topics in fusion as reported in subsection 2.3.

The fields of turbulence transport and fast ions are closely knit. With steep gradients in plasma equilibrium parameters and with populations of energetic ions far from thermal equilibrium, fusion plasmas have considerable free energy. This energy drives turbulence, which in turn acts back on the equilibrium profiles and on the dynamics of the fast ions. The turbulence naturally gives rise to enhanced transport, but also sets up zonal flows that tear the turbulent structures apart and result in transport barriers. The edge transport barrier being most likely at the root of the poorly understood, but experimentally reliably achieved, high confinement mode (H-mode). This non-linear interplay between turbulence and equilibrium also supports transient events reminiscent of edge localised modes (ELMs) where energy and particles are ejected from the plasma edge in intermittent bursts.

This set of topics is the focus of our fusion plasma physics research: With first-principles based codes we seek to model the interplay between plasma turbulence, transport and equilibrium. This modelling is tested against experimental data in collaboration with other fusion plasma physics institutes. To elucidate the physics of fast ions and their interplay with turbulence, waves and transient events, we are engaged in the diagnosis of confined fast ions by collective Thomson scattering (CTS) at the TEXTOR tokamak at the Research Centre Jülich and at the ASDEX upgrade tokamak in the Max-Planck Institute for Plasma Physics in Garching, both in Germany.

2.2 Turbulence and transport in fusion plasmas

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The transport of heat, particles, and momentum across the confining magnetic field of fusion plasmas is one of the most important, but also most difficult areas of contemporary fusion research. It is well established that the “anomalous” transport component due to low frequency turbulence is usually far larger than the classical and neo-classical collisional transport, in particular in the edge region. Therefore it is of highest priority to achieve a detailed understanding of anomalous transport and the underlying turbulence for the design of an economical viable fusion reactor based on magnetic confinement schemes. In spite of the dramatic progress in experiment, theory and computations during recent years the quantitative understanding is still sparse and lacking predictive capability. Even fundamental phenomena such as transitions from low confinement regime (L-mode) to high confinement regime (H-mode), the profile resilience and the particle pinch that are routinely observed and classified experimentally have no generally accepted explanations.

The activities within plasma turbulence and transport are mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas, but also investigations of core turbulence and transport are taken up. Generally, it is acknowledged that the conditions near the edge of the plasma are dictating the global performance, which seems natural since all transport has to go through the edge region, but certainly the coupling to the core plasma dynamics is essential. Theoretical and numerical investigations of first principle models form the majority of the work performed. We emphasize benchmarking of results and performance, both with other codes and analytic results (verification) and then also with experimental observations (validation).

Our activities are fully integrated into the EURATOM fusion program, and we have active collaborations with several EURATOM laboratories on theoretical issues as well as on direct comparisons of our results with experimental observations. We are strongly involved in the EFDA-JET program, with V. Naulin being task force co-leader of Task-Force Transport. We are actively participating in the Integrated Tokamak Modeling (ITM) Task Force on validation and benchmarking of codes as well defining the ITM data structures. Furthermore, we have a significant involvement in the new initiated EFDA Topical Groups, and have obtained several task agreements particularly within the TG Transport.

Several of our numerical codes are in use at different European laboratories, where they are employed for specific purposes, ranging from experimental comparisons to education of students.

In the first week of September, we organized and hosted the "13th EU-US TTF workshop 2008 and 1st EFDA Transport Topical Group Meeting". The workshop was held in Copenhagen with around 100 participants mainly from Europe and USA.

The work carried out through 2008 included the following items:

- The involvement in the JET work program is described in Sec. 2.2.1. It is mainly focused on modeling and simulations. It comprises investigations of the power deposition of ELMs, explaining the observed asymmetric power deposition; characterization of the structure and dynamics of ELM filaments by using the signals from magnetic probes and forward modeling; modeling of toroidal and poloidal momentum transport and comparison with experimental observations showing evidence for inward toroidal momentum convection.
- Investigations of the turbulence and transport at the edge and SOL of toroidal plasmas by participating in experimental investigations and applying edge-SOL turbulence codes. It is well established that the turbulence and transport in the edge and SOL of toroidal plasmas are strongly intermittent and involve outbreaks of hot plasma. These structures, often referred to as "blobs", are formed near the last closed flux surface (LCFS) and propagate far into the SOL. They have a profound influence on the pressure profiles in the SOL, the ensuing parallel flows, and the power deposition on plasma facing components. In Sec. 2.2.2 we describe the application of the ESEL model and the comparison with experimental results obtained in different devices. In addition, we discuss the extensions of the ESEL code. In 2.2.3 we present an initial stage towards a 3D toriodal code, the DIESEL code, where the interchange dynamics is solved on disk geometry with several disks distributed in the toroidal direction and coupled parametrically along the magnetic field lines. Temperature fluctuation measurements in TCV are presented in Sec. 2.2.4 together with initial comparisons with the results from ESEL. Finally, Sec. 2.2.8 describes our involvement in experimental investigations of ELM filament propagation in ASDEX

UG with particular attention to measuring the magnetic perturbations in ELM filaments.

- To extend our turbulence modeling in the edge/SOL we are deriving gyro-fluid and gyro-kinetic models for the edge/SOL dynamics as generalizations of electrostatic, cold ion, ESEL-like models (see Sec. 2.2.2 – 2.2.3). Motivated by observations of strong time dependent radial electric fields in the edge region in several tokamaks, the models are being extended to account for both large electric fields and electromagnetic effects, see Secs. 2.2.5 - 2.2.7.
- The spontaneous formation of flows in turbulence is an important topic in fusion research. We have investigated various aspects of toroidal as well as poloidal flow generation and of the related transport of momentum. As discussed in Sec. 2.2.1 we are involved in the investigations of momentum transport at JET. Section 2.2.9 discusses the theoretical aspects of generating nonlocal geodesic acoustic modes (GAMs) by drift waves and their coupling to zonal flows.
- Examples of our involvement in the ITM activities are provided in Sec. 2.2.10.

2.2.1 Participation in the JET work programme

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Risø DTU participates in the EFDA JET work programme through a number of activities, mostly focused on modelling and theory. In 2008 the work included the following topics:

ELM power deposition and asymmetries

Edge Localized Modes, ELMs, are one of the most limiting factors to tokamak operation. They result in high and unsustainable power loads on plasma facing components for any realistic reactor design that uses H-mode plasmas. Thus, the understanding of their dynamics is a necessity for operation of fusion devices and in turn for controlling ELMs. One difficult to understand feature of ELM power deposition is that although the ELMs originate dominantly on the low field side, most of the power is deposited on the divertor plates facing the high field side. Assuming, however, that the plasma expelled from the last closed flux surface on the low field side keeps its parallel momentum, this feature may easily be understood. Modelling ELM power deposition profiles with a free streaming along magnetic field lines, described by a shifted Maxwellian distribution, results in improved agreement with experimental observations. These results have been presented at PSI and IAEA conferences. Experiments to influence edge rotation to quantify the effect are underway.

ELM characterisation from magnetic signals

Many tokamaks are equipped with a large number of magnetic probes. These are most often used for equilibrium reconstruction and to identify MHD modes. During ELMs strong magnetic signals are observed. Using a simple model for the current in a moving ELM filament several properties of type I ELM filaments could easily be recovered, such as the number of filaments in ELM events, radial velocity, toroidal velocity, toroidal deceleration and current [1]. These quantities are depicted in Figure 1 for ELMs detected at JET. It is suggested that magnetic probes should be used to give a more detailed reconstruction of the current structure of the plasma edge.

1. P. Migliucci and V. Naulin, letter submitted to Nuclear Fusion (2008).

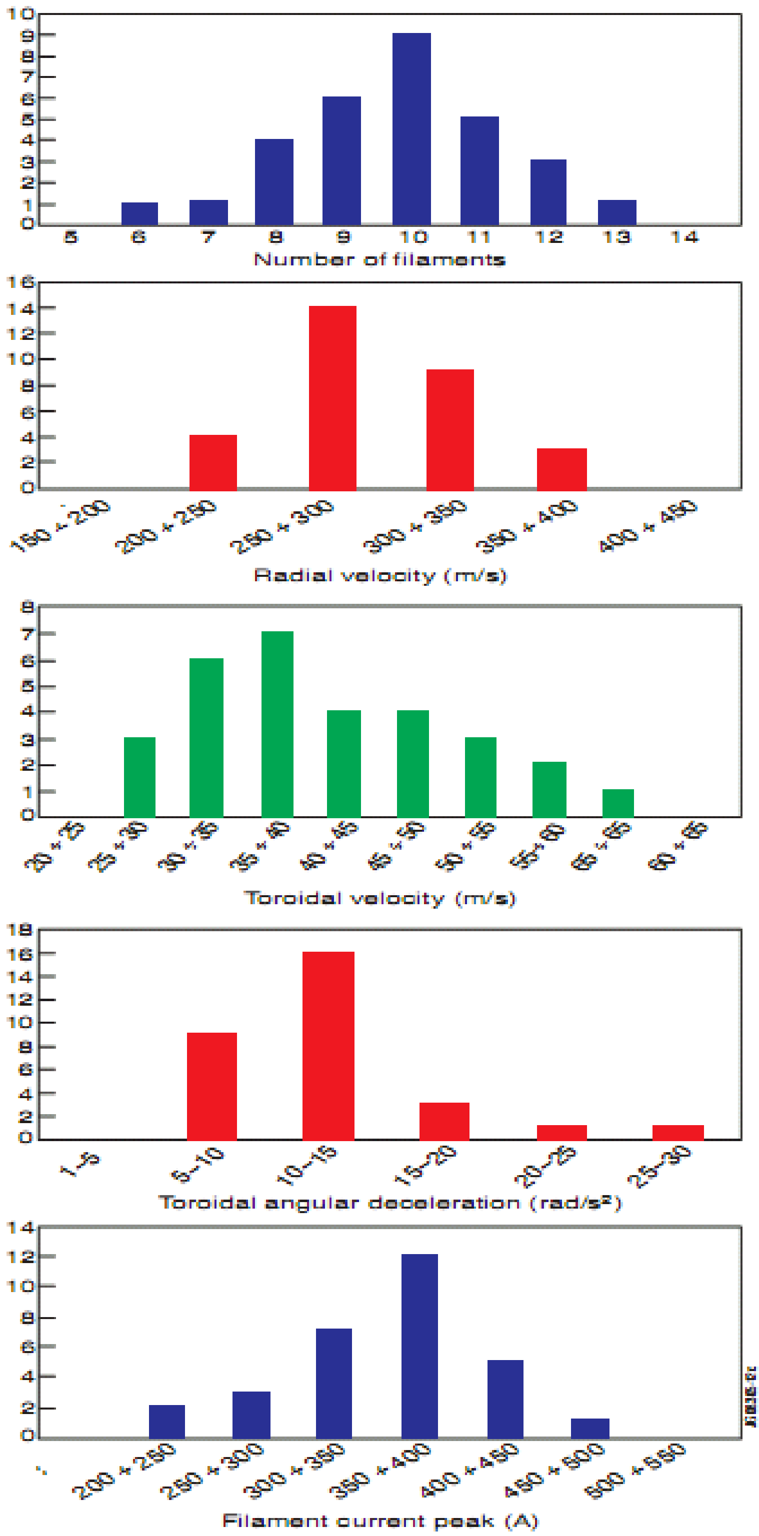

Figure 1. Histograms of ELM properties from magnetic forward modeling.

Evidence of inward toroidal momentum convection in the JET Tokamak

Plasma rotation and momentum transport in tokamaks are presently an active research area. Sheared rotation leads to quenching of turbulence and improvement in confinement. Toroidal rotation increases stability against pressure limiting resistive wall modes. Extrapolating toroidal rotation, in magnitude and profile to future tokamaks, such as ITER, remains a challenge, as neither momentum transport nor sources are known precisely.

Neutral Beam Injection (NBI) power and torque was modulated on JET. Typically 5 MW of NBI power was modulated, out of a total of 10 to 15 MW. Figure 2 compares experimental data and simulations for the amplitude A and phase φ of the toroidal rotation. For the simulations two options for the momentum diffusivity χ_ϕ or Prandtl number Pr and momentum pinch v_{pinch} are considered: case (i) fix Pr=0.25 to yield χ_ϕ = $0.25\chi_{i,eff}$ ($\chi_{i,eff}$ is the effective ion heat diffusivity) and v_{pinch}=0 and case (ii) match the simulated and experimental phase by fitting Pr, and vary the v_{pinch} profile.

Case (i) with Pr = 0.25 and v_{pinch}= 0 clearly shows that this assumption is not compatible with the experimental data. Case (ii) uses Pr = χ_ϕ/χ_i~1 and v_{pinch} varying radially between 0 and –25 m/s. The v_{pinch} profile reproduces best the experimental amplitude and phase profiles, together with an acceptable reproduction of the steady-state toroidal rotation profile. These results yield the first experimental evidence of an inward momentum pinch on JET and also show evidence of a high Prandtl number Pr = $\chi_\phi/\chi_i \approx 1$ [1].

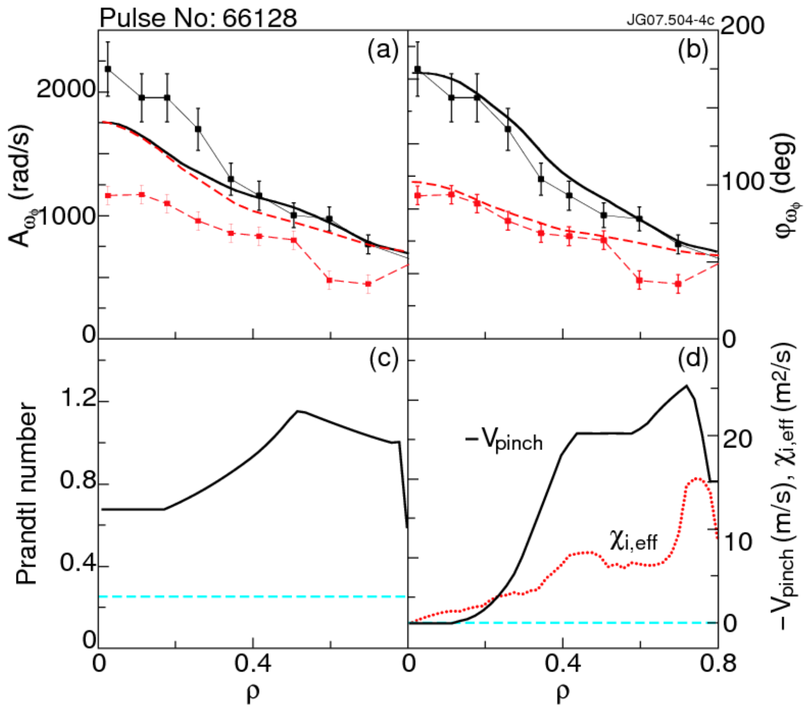

Figure 2 Comparison of the experimental amplitude (black solid with error bars) and phase (red dashed with error bars) and simulated amplitudes $A_{\omega,\phi}$ (black solid) and phases $\varphi_{\omega,\phi}$ (red dashed) of modulated ω_ϕ in frame (a) case (i) with Pr = 0.25 and v_{pinch}= 0 and frame (b) case (ii) with Pr ≈ 1 and v_{pinch} taken from figure (d) (black solid). (c) Prandtl numbers and (d) pinch velocity profiles used in cases (i) (blue dashed) and (ii) (black solid). Also shown the used $\chi_{i,eff}$ (red dotted) in frame (d).

1. T. Tala, K.D. Zastrow, J. Ferreira *et al.* Phys. Rev. Lett. **102,** 075001 (2009).

2.2.2 Edge/SOL modelling

A. H. Nielsen, J. Juul Rasmussen, V. Naulin, J. Madsen, O. E. Garcia (Department of Physics and Technology, University of Tromsø, Norway), R. A. Pitts (ITER), J. Horacek, Jakub Seidl*, (*Institute of Plasma Physics, Prague, Czech Republic), Arturo Alonso (EFDA-JET, Culham Science Centre, Abingdon, OX14 3DB, UK), M. Vergote (Laboratory for plasma Physics, Brussels, BELGIUM) and W. Fundamenski (EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, UK)*

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Several other instituteswithin EURATOM are now applying the ESEL code, which simulates nonlinear interchange dynamics on the outboard mid-plane of toroidal devices. The motivation for running the code under different conditions, close to the ones found in the respective plasma experiments, is to obtain spatially resolved turbulence data, to study the EDGE/SOL dynamics numerically in greater detail, and more importantly to perform comparison of the code data with measurements, which will reveal the parametric boundaries of the ESEL model. At the moment ESEL is or has been applied to the following devices:

TCV, CRPP, Lausanne, Switzerland, see also section 2.2.4.

CASTOR, IPP, Prague; Czech Republic

JET, Culham, England

MAST, Culham, England

TEXTOR, Jülich, Germany

We are planning to address the TJ-II in Madrid in the near future.

From our side we stay in close contact with the above groups and our numerical codes are now under version control enabling the groups to have easy access to the latest version of the codes. In November 2008 we were hosting a small Workshop on Edge/SOL modeling with particular attention to the ESEL code. The agenda contained a combination of development of experimental works with the numerical codes in addition to seminars on both theoretical background work and on various results from the ESEL simulations in different settings.

We have specifically been employing the ESEL code to investigate the correlation properties of the fluctuations and the fluctuation induced momentum, particle and heat transport. We have developed and included routines for calculating the trajectories of a large amount of passive tracers (up to 500.000 tracers per simulation) in the velocity field of ESEL. Hereby we are able to study transport mechanism and single transport events in details. Furthermore we use the numerical probes, which measure all relevant quantities; density, temperature and electric potential to calculate the cross correlation between 2 probes of different distance. From the time delay and width of the cross-correlation we can estimate velocities and sizes of blobs, which are the carriers of momentum, particle and heat transport, see Figure 3.

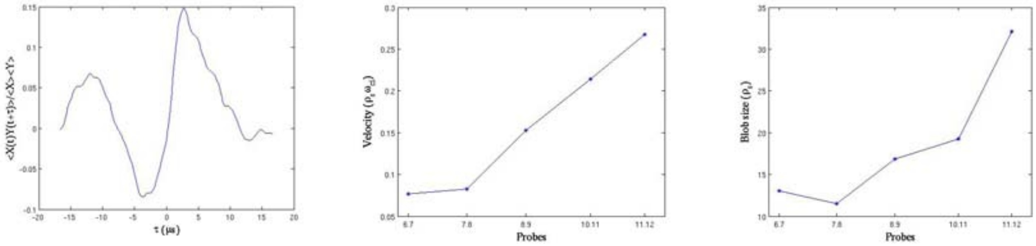

Figure 3 a). Cross-correlation of the particle density fluctuation between 2 closely radial spaced probes located near the last closed flux surface. b) and c) are the measured blob velocity and size based on correlations for probes locate in the SOL. Plasma parameters relevant for TCV has been used.

ESEL is formulated in vorticity, density and electron temperature as dependent variables. Our model includes diffusive effects on all quantities ensuring conservation of overall particle and temperature due to this effect. Unfortunately this does not result in energy conservation. During 2008 we have developed an extended version of the ESEL model (BESEL), where we use electron pressure instead of electron temperature as dependent variable; to ensure energy conservation. The effect on energy conservation is shown in Figure 4, where we show two different simulations of BESEL and ESEL, respectively. The improvement is clearly visible.

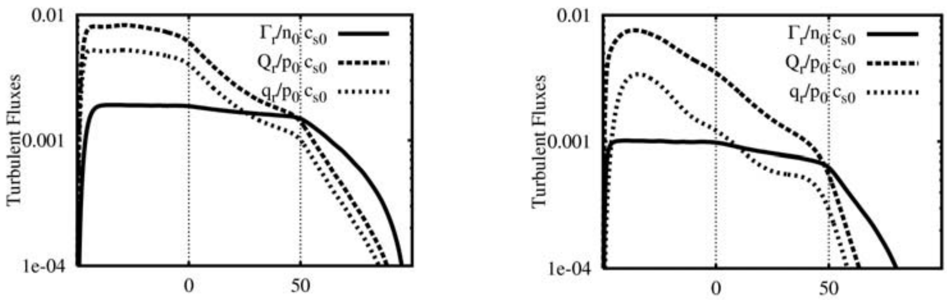

Figure 4. Radial profiles of turbulent radial fluxes of particles and energy averaged in time and poloidal direction as calculated by the BESEL (left) and ESEL (right) code for typical TCV conditions

2.2.3 DIESEL: a toroidal numerical code

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The DIESEL code is an extension of the ESEL code, see section 2.2.3. It solves an interchange model in 3D toroidal geometry with magnetic field configuration that mimics a tokamak configuration, where the toroidal direction is divided into a number of drift planes. On each drift plane the equations are solved on a disk domain corresponding to the full 2D cross section and communicate parallel with the nearest drift planes using parameterized velocities, the ion sound speed, C_s for the density equation and the Alfvén speed V_A for the vorticity equation.

On the individual drift planes the solutions are employing a modified version of the Risø developed Disk code, [1]-[2], which is parallelized and optimized on a distributed memory machines like a Linux cluster. For individual drift planes we observed a linear speedup in the order of 100 CPUs. Each drift plane is connected parallel point-by-point taken account of an arbitrary specified q-profile. The parallel direction is well suited to be parallelized and the numerical code is able to use well above 1.000 CPUs. Figure 5 displays the speedup as a function of the total number of CPUs for 4 different numbers of drifts planes using a moderate perpendicular resolution of 1024x2048 points. The simulations were performed on the Risøl Linux cluster, Aiolos, which uses Infiniband as interconnects.

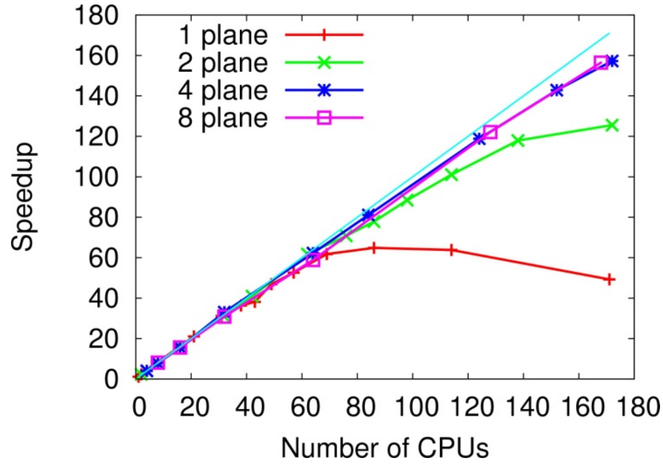

Figure 5. The speedup of DIESEL as a function of the total number of CPUs using a perpendicular resolution of 1024x2048.

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2. H.J.H. Clercx, A.H. Nielsen, D.J. Torres and E.A. Coutsias, Eur. J. Mech. B - Fluids **20,** 557 (2001).

2.2.4 Fast temperature fluctuation measurements in SOL of tokamak TCV

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A fast scanning assembly has been widely used on the TCV tokamak to insert a probe head equipped with an array of single Langmuir probe tips up to the separatrix at the plasma midplane. Using fast voltage sweeping, we obtain IV-characteristics every 8 µs, allowing an estimate of the electron temperature, T_e, on this timescale. Since this temporal resolution corresponds to typical T_e autocorrelation times [1]-[2], it is just fast enough to resolve the temperature of individual turbulent structures (blobs).

Since at this voltage sweep frequency (~60 kHz) hysteresis is observed in the IV-characteristics, some effort is required to demonstrate the credibility of the T_e derived from the characteristics. Following the methodology proposed in [3], we use both numerical and lab simulations of the equivalent probe circuit, together with a simplified plasma circuit to study the capacitative coupling both across the plasma sheath and in the probe circuit itself. Comparisons are also made between the results from higher frequency sweeping and the standard values derived from a slower sweep to show that the fast measurement is reliable.

Considerable effort has been expended in recent years to compare the statistical character of turbulence in the SOL particle flux on TCV, with results from the 2D fluid electrostatic model ESEL [2], [4]. Using results from the fast sweeping, similar comparisons can now be made with the fluctuating T_e and will be described in this contribution. We also present basic statistics derived from the T_e time series obtained at different radii in the SOL plasma and show, in particular, that the relationship between higher moments of the probability distribution function from both experimental and simulated T_e's may be well described by the Beta probability distribution function, introduced for SOL turbulence in [5]. The fast T_e capability also allows the SOL response to Edge Localized Modes (ELMs) to be studied and new results will be presented for the far SOL T_e response during Type III ELMs.

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5. B. Labit etal., Plasma Phys. Contr. Fusion 49 (2007) 12B 281

2.2.5 Guidingcenter model

J. Madsen, J. Stærk, V. Naulin, J. Juul Rasmussen, A. H. Nielsen and T.S. Hahm (PPPL, Princeton, USA)
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The trajectory of a charged particle in an electromagnetic field is in general very complex. When the spatial and temporal variation of the fields is slow compared to the Larmor radius and the gyration frequency, the guiding center approximation can be applied. In an approximate sense the guidingcenter approximation decouples the gyro-orbit motion from the slow dynamics of the “guidingcenter”. This decoupling implies that the effective dimensionality of the problem is reduced from six to four.

The guiding center approximation is well described in nearly all introductory textbooks on plasma physics. However, in these classical presentations one simply explicitly “averages out” the gyromotion. In our contribution we present guidingcenter coordinates derived using a modern geometric Lie transform method [1]. The Lie transformation method automatically guarantees properties such as phase space conservation, energy conservation of the guidingcenter magnetic moment and gyro-gauge invariance. The calculations are less cumbersome when going to second and third order. The method furthermore provides explicit expressions of the generating vector field of the Lie transformation, which can be used in pull-back representations of fluid moments.

Second order gyrogauge invariant guidingcenter coordinates with a strong electric field present have been derived. Compared to earlier work [2,3,4] our result takes a simpler form and is the first result that derive the guidingcenter coordinates using the Lie transform method with strong electric fields present. The simplified coordinates make numerical and analytical analysis simpler. Furthermore, we have derived a Vlasov-Poisson model with a corresponding global energy theorem; this guidingcenter model can be used to study situations with mesoscale turbulence and strong flows. This work is also important because the modern gyrokinetic formalism is derived from the guidingcenter approximation.

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2.2.6 A nonlinear electromagnetic gyrokinetic model for edge/SOL

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Understanding tokamak microturbulence is necessary for understanding the tokamak transport physics. The nonlinear gyrokinetic formalism has provided a theoretical framework for recent advances in the understanding of tokamak microturbulence [1]. The original scope of application was core turbulence. Core turbulence is characterized by having small fluctuation amplitudes and a clear separation of the macroscopic and microscopic length scales. In the edge region the relative fluctuation amplitude is no longer small. The relative fluctuation amplitude even approach unity in the SOL. Also, steep gradients are found in the equilibrium profiles and strong shear flows are typically observed in the pedestal and near ETB's. No clear separation of the microscopic turbulence and the equilibrium length scales exists. In the contribution 2.2.7 the strong background electric field was assumed stationary. An extension where the strong sheared electric field is time-dependent and self consistently determined is being developed. This model is somewhat different because we transfer the magnetic fluctuations into the symplectic part of the Lagrangian, meaning that the particle reference frame is co-moving with the gyrocenter drifts that arise from the magnetic perturbation. It turns out that this approach has some computational advantages especially in the Amperes equation. We have also studied cases where the particle reference frame moves with the fluctuating **E**x**B** drift. This approach reintroduces the polarization drift into gyrokinetics, but simplifies the gyrokinetic Poisson equation. Future studies will investigate whether this approach is advantageous.

We have also carried out an introductory investigation the statistical properties of tracer particles with large ion Larmor radii in a turbulent flow. It is believed that finite Larmor radius effects are important for fast particles in the edge/SOL region, because gradients vary substantially over an ion gyro radius. We have obtained promising preliminary results from calculations based on synthetic turbulent flows. The goal is to combine the ESEL and/or TYR code with the particle tracer code.

1. A. Brizard and T.S. Hahm. Reviews of Modern Physics, **79,** 421 (2007).

2.2.7 Fully electromagnetic nonlinear gyrokinetic equations for tokamak edge turbulence

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An energy conserving set of the fully electromagnetic nonlinear gyrokinetic Vlasov equation and Maxwell's equations, which is applicable to both L-mode turbulence with large amplitude and H-mode turbulence in the presence of high **E**x**B** shear has been derived. The phase-space action variational Lie perturbation method ensures the preservation of the conservation laws of the underlying Vlasov–Maxwell system. Generalized ordering takes $\rho << L_E \sim L_p << R$ here ρ is the thermal ion Larmor radius, as typically observed in the tokamak H-mode edge, with L_E and L_p being the radial electric field and pressure gradient lengths. $k\rho \sim 1$ is assumed for generality, and the relative fluctuation amplitudes $e\delta\varphi/T_i \sim \delta B/B$ are kept up to the second order. Extending the electrostatic theory in the presence of high **E**x**B** shear [1], contributions of electromagnetic fluctuations to the particle charge density and current are explicitly evaluated via pull-back transformation from the gyrocenter distribution function in the gyrokinetic Maxwell's equation.

1. T.S. Hahm, Phys. Plasmas **3**, 4658 (1996).

2.2.8 Local magnetic perturbations in the ASDEX Upgrade scrape off layer

N. Vianello, V. Naulin, R. Schrittwieser**, H.W. Müller***, C. Ionita**, M. Zuin*, F. Mehlmann**, J.J. Rasmussen, V. Rohde***, R. Cavazzana* (* ENEA, Consorzio RFX, Padova, Italy) M. Maraschek*** (***IPP, Max-Planck-Institute for Plasma Physics, Garching, Germany), C. Lupu** (**Institute for Ion Physics and Applied Physics, University of Innsbruck, Austria) and the ASDEX Upgrade Team*
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ELM events are accompanied by drops in the plasma current. A part of the current lost seems to be convected out from the last closed flux surface in the plasma filaments released during an ELM. The amount of current in these filaments is therefore an additional - besides density, temperature, and size - parameter to characterise ELMs. Moreover measuring the current in ELM filaments gives information about the plasma pedestal at the time of the instability, and thus allows conclusions on the ELM mechanism itself.

For accurate measurements it is necessary to access all three spatial components of the magnetic field perturbation as close as possible to the current distribution, to get a clean signal. To that purpose three orthogonal magnetic pickup coils were introduced into the head for the reciprocating midplane manipulator on ASDEX Upgrade. The probe head is depicted in Figure 6 [1].

This allows to measure plasma density and potential fluctuations as well as the magnetic fluctuations simultaneously, and thus to link current and density perturbation in the filaments. The first data (see Figure 7) have been obtained during the 2008 campaigns and are presently under evaluation.

1. C. Ionita, N. Vianello, H.W. Müller *et al.* J. Plasma Fusion Res. SERIES, **8,** 413 (2009)

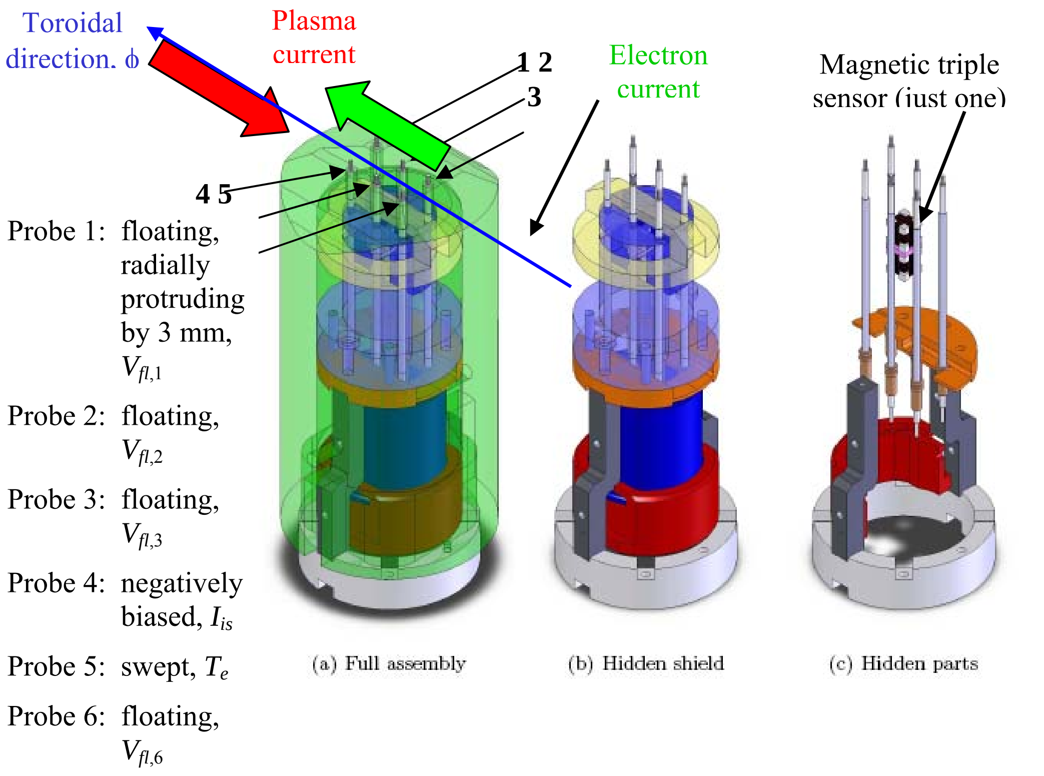

Figure 6. Probe head for simultaneous measurements of the three components of the magnetic field perturbations, the ion saturation current and the potential.

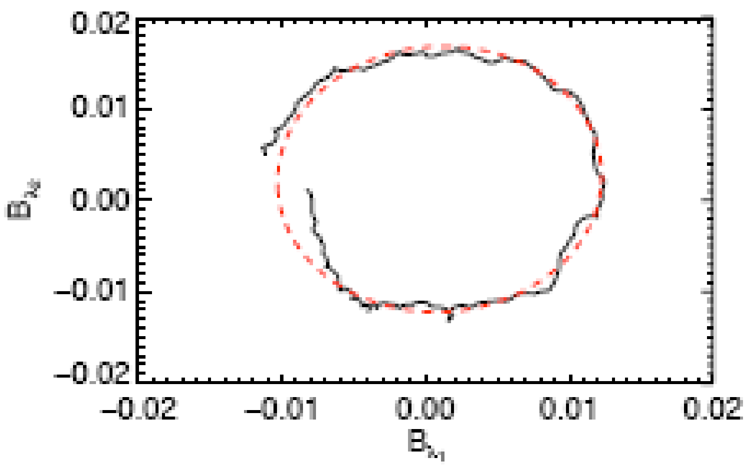

Figure 7. Magnetic field trajectory, i.e., the two components of the magnetic field perturbation in the plane perpendicular to the current.are plottet against each other during an ELM

2.2.9 Nonlocal theory for the excitation of Geodesic Acoustic Modes by drift waves

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Geodesic acoustic modes (GAMs) are low frequency toroidal modes, which are primarily electrostactic and are typically observed in the edge region of tokamak plasmas, see e.g. [1]. GAMs are believed to be excited by nonlinear processes and have been found to play an important role in connection with the generation of zonal flows by low frequency turbulence and are thereby of a key player in the understanding of turbulent transport, see, e.g., [2]. We have investigated the nonlocal excitation of GAMs in inhomogeneous plasmas typical of the edge region of tokamaks. The continuum GAMs with coupling to drift waves are found to create discrete "global" unstable eigenmodes localized in the edge pedestal region of the plasma and multiple resonantly driven unstable radial eigenmodes can coexist on the edge pedestal. These results appear to be in agreement with recent experimental findings [3].

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3. G.D. Conway et al. Plasma Phys. and Control. Fusion 50, 085005 (2008).

2.2.10 Participation in ITM-activities

J. Madsen, V. Naulin, A. H. Nielsen, J. Juul Rasmussen, B.D. Scott, A. Bottino* (*Max-Planck-Institut für Plasmaphysik, Garching, Germany) and D. Reiser (Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, Jülich, Germany)*
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The participation in the Integrated Tokamak Modeling (ITM) activities has mainly been concentrated in the working group IMP4. The main topic has been to port the common data structure, the freeware software HDF5, to our numerical codes. Risø DTU was hosting a mini workshop (January 28 – February 1).involving, beside the Risø group, IMP4 taskforce leader Bruce Scoot and Dirk Reiser. During the workshop we closely discussed our numerical scheme in general and HDF5 in particular. Additionally, we also participated in the Annual General Integrated Tokamak Modeling Task Force meeting held 10-12 September in Frascati.

As a test for exchanging data between different groups and codes we have set up an ongoing project studying the simple case of the dynamics of a density perturbation localized in the edge region of a medium size tokamak in a full 3D geometry. The 2D evolution of such a perturbation has been studied in details on the low-field side, where the gradient of the magnetic field always points radially inward, see e.g. [1-2]. Here, the initial condition is implemented in two different 3D numerical codes, ATTEMPT [3], and a new developed code, DIESEL (see section 2.2.3).

The ATTEMPT code has been employed to study the blob dynamics in a full 3D tokamak geometry including both the edge and SOL region. Previous studies with the ATTEMPT code proved that density blobs appear for typical parameters of the TEXTOR tokamak. The code has been prepared for flux driven simulations with detailed control of the blob initial state. The results show that a decrease of Alfvénic interaction of electric potential and current density leads to the expected radial blob motion. This is to be expected in the SOL and the first results are in agreement with previous studies, [1] based on simplified 2D-models and approximate closures for the Alfvénic interaction. The work aims at a detailed understanding of the dependence of blob motion on collisionality and SOL boundary conditions at the plasma material boundaries. The results of the DIESEL code, solving an interchange model in a toroidal geometry, are used as comparison with the results from ATTEMPT code. In Figure 8, we show the density and vorticity distribution for a blob initially concentrated in radial, poloidal and toroidal directions.

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2. W. Fundamenski, O.E. Garcia, V. Naulin, R.A. Pitts, A.H. Nielsen, J. Juul Rasmussen, J. Horacek, J.P. Graves and JET EFDA contributors. Nucl. Fusion **47** 417-433 (2007)
3. D. Reiser, PoP 14, 082314 (2007)

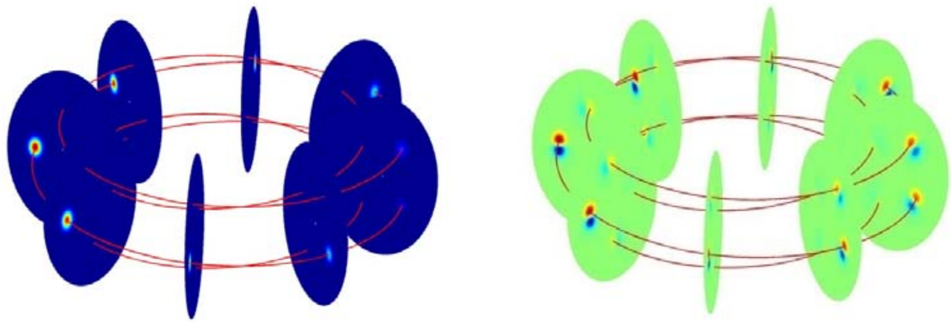

Figure 8. Blob simulation in DIESEL using 8 drift planes and (constant) q=3. As initial condition we implemented a density blob, Gaussian distributed both parallel and perpendicular. Left figure shows the density distribution and right the vorticity distribution just after the initialization.

2.3 Millimetre waves used for diagnosing fast ions in fusion plasmas

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Millimetre waves, corresponding to frequencies in the 100 GHz range, permit probing and imaging on the centimetre scale and transmission of signals with bandwidths in excess of 10 GHz. Coherent sources are now available from the micro- to megawatt range, CW.

In the world of fusion, millimetre waves are used extensively both as a diagnostic tool and for heating and manipulating the plasma locally as well as globally. Central to achieving these objectives is the fact that millimetre waves, like laser light, can be projected in narrow focused beams, but unlike laser light, the millimetre waves can interact strongly with the plasma.

At Risø DTU, millimetre wave diagnostics for measuring the velocity distribution of the most energetic ions in fusion plasmas are developed and exploited. The measurements have spatio-temporal resolutions on the centimetre and on the millisecond scales.

The most energetic (or fastest) ions are the result of fusion reactions and auxiliary heating. Their interaction with the bulk plasma is the main mechanism by which the fusion plasmas reach and sustain the high temperatures of 100-200 million degrees Kelvin required for fusion. The considerable energy associated with the fast ions can also drive turbulence and cause instabilities in the plasma, and hence degrade the confinement of the plasma and of the fast ions themselves. Understanding and controlling the dynamics of fast ions are central tasks in the development of fusion energy and one of the main research topics for the next large fusion facility, ITER. It is a task we seek to contribute to by developing and exploiting the unique diagnostic capability of millimetre wave based collective Thomson scattering (CTS). In 2008 the importance of the fast ion CTS diagnostic was further underlined by the fact that it is now included in the ITER baseline design.

In addition to the use of CTS to diagnose the fast ions, the diagnostic technique may also be used to measure the fuel ion or isotope ratio in a fusion plasma – both temporally and spatially resolved. The Risø DTU CTS group has taken up the responsibility for an EFDA task investigating the feasibility of such a fuel ion ratio diagnostic. While the task was undertaken in 2008, the first results will be published in 2009 and will thus not be reported further in this report.

The group has developed and implemented fast ion CTS diagnostics at the TEXTOR and ASDEX Upgrade tokamaks, which are located at the Research Centre Jülich and at the Max-Planck Institute for Plasma Physics in Garching, both in Germany. These CTS projects are conducted in collaboration with the Max-Planck Institute for Plasma Physics in Garching and the TEC[1] consortium. Up to 2008, the collaboration also included the Plasma Science and Fusion Center at MIT (USA). While they had to withdraw due to financial circumstances, the contact is still maintained.

The upgraded CTS system for TEXTOR was brought into operation in 2005 where the first results were obtained. In 2008, the experimental CTS campaigns of the previous years were continued. An overview of the campaigns and results is found in subsection 2.3.1. In addition to the fast ion CTS measurements, the Risø DTU group's involvement at TEXTOR has also lead to participation in a related project in collaboration with FOM, including new use of the CTS receiver. This project is described in subsection 2.3.2.

The activities of the group at ASDEX Upgrade, including the commissioning, first fast ion experiments, and tests and improvements of the receiver electronics are presented in subsections 2.3.3 – 2.3.8.

The proposed fast ion CTS system for ITER and the development of the design and of components relevant to ITER CTS are described in subsections 2.3.9 – 2.3.18, alongside modelling of neutronics and measurement capability.

1 TEC: the Trilateral Euregio Cluster, comprising Association EURATOM-Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Jülich, Germany; Association EURATOM-FOM, Institute for Plasma Physics, Rijnhuizen, The Netherlands; and Association EURATOM-ERM/KMS, Belgium.

Finally, a brief description of the group's involvement in CTS experiments at other machines is given in subsection 2.3.19.

2.3.1 Overview of results from CTS at TEXTOR

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In 2008, the exploitation of the fast ion CTS diagnostic at TEXTOR was continued, as a number of physics campaigns were conducted. The emphasis of the fast ion CTS campaigns were on three primary topics: Fast ions in ICRH heated plasmas, Fast ion transport during sawtooth crash, Comparison between fast ion CTS and fast ion charge exchange spectroscopy. These results are briefly described below:

Fast ions in ICRH heated plasmas

Measurements of confined fast ions in TEXTOR plasmas with a number of different ICRH power levels were done in 2008. TEXTOR plasmas with an electron density of 3 10^{19} m^{-3} and a magnetic field of 2.6 T were used and 38 MHz ICRH waves with power levels of 300, 500, and 800 kW were applied. In Figure 9, the time traces of a fast ion channel are shown (111.1 GHz) for three similar discharges with different ICRH power levels. In the beginning of the measurement window, co-NBI is applied, and the ICRH is ramped up from 1.6 s to 1.7 s while the NBI remains switched on. Before ICRH is applied, the spectral power density in the fast-ion channel shown fluctuates around a level of 0.5 eV due to the presence of fast NBI ions. When ICRH is applied at 1.6 s, the signal in the fast-ion channel is seen to increase in all three discharges. When 300 kW of ICRH is applied, the spectral power density is increased to around 0.75 eV whereas the level is around 1 eV and 2 eV for the 500 and 800 kW cases, respectively. The velocity distributions obtained from these data will be compared with ICRH power coupling codes in 2009.

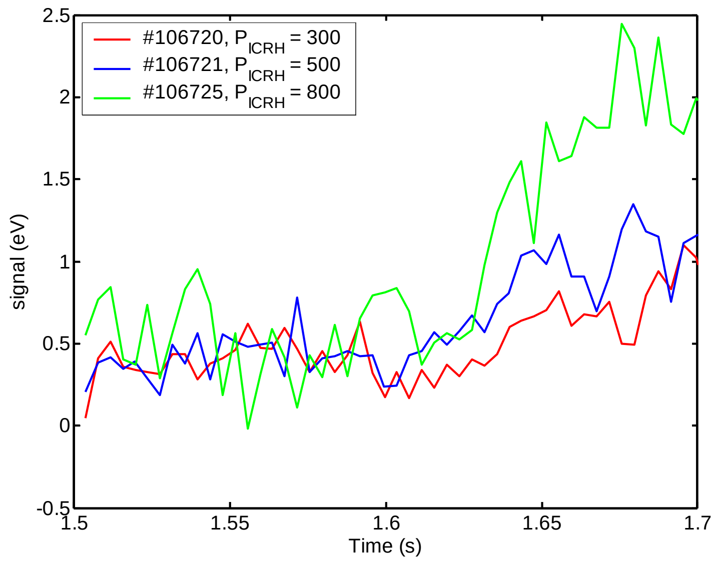

Figure 9. Time traces of a fast ion channel are shown (111.1 GHz) for three similar discharges with different ICRH powers.

Measurements of the fast ion populations due to ICRH have also been performed at various radial positions and for various resolved pitch angles. When comparing the fast-ion velocity distribution before and after application of ICRH, it is found that the increase of the fast-ion density with a velocity component perpendicular to B is larger on the tokamak low field side compared to the high field side of the ICRH resonance. These data are to be compared with detailed ICRH simulations in 2009.

Fast ion transport during sawtooth crash

The fast ion confinement during sawtooth oscillations has been measured in the centre of co-NBI heated TEXTOR plasmas. Both the fast ion distribution projected close to perpendicular to the magnetic field and the fast-ion distribution projected close to parallel to the magnetic field has been investigated. A strong anisotropy was found in both the fast ion velocity distribution and in the redistribution of the fast ions. In the near parallel projection (around 30 degrees to the magnetic field), fast ions with velocities above 2 10^6 m/s have been measured whereas the velocity distribution perpendicular to the magnetic field showed a significantly lower super-thermal contribution. During the sawtooth crash, a reduction of the parallel fast ion velocity distribution up to 50% was measured whereas no significant changes were seen in the perpendicular velocity distribution. Indications of pitch angle scattering of fast ions during the sawtooth collapse are also seen and a finalization of the analysis and publication are expected in 2009.

Comparison between fast ion CTS and fast ion charge exchange spectroscopy

At low electron density, the charge exchange recombination spectroscopy (CXRS) system at TEXTOR may also be used to measure the confined fast ions. Discharges have been performed where the CTS fast ion diagnostic and the CXRS diagnostic simultaneously measured the fast ion distribution at a number of radial positions during balanced NBI injection. Analysis of these measurements is ongoing, and the first comparison results show good agreement between the two diagnostics.

2.3.2 Island studies during 140 Ghz gyrotron operation

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The observation of microwaves from fusion plasmas plays an important role in many diagnostic and plasma control applications. In the ECE range of frequencies, both electron temperature diagnostics and diagnostics facilitating the use of scattering operate. On TEXTOR, an ECE radiometer has been installed in order to detect tearing modes and, together with the ECRH system, to suppress such modes. This radiometer shares the transmission line with the ECRH system and is operated by FOM. This in-line system has been tested successfully under a range of plasma conditions. However, under some circumstances, i.e. when ECRH is applied and a rotating island is present in the plasma, strong signals have been observed in the in-line radiometer. The origin of this signal is at present unknown and under investigation in collaboration between FOM and Risø DTU. In this collaboration, the CTS receiver of Risø DTU operating at TEXTOR was modified to detect frequencies in the vicinity of 140 GHz, which is the frequency range of the FOM in-line system. In this way, the origin of the strong signals has been investigated by the use of both receiver systems. The high frequency resolution of the CTS receiver system is sufficient to reveal detailed structures in the detected signal as Figure 10 demonstrates. In this case, the island passing frequency is around 200 Hz, and the present time window shows ten passing islands. At each island passage, several characteristic frequencies appear which exhibit a chirping behaviour. The analysis of these results is ongoing in collaboration between FOM and Risø DTU.

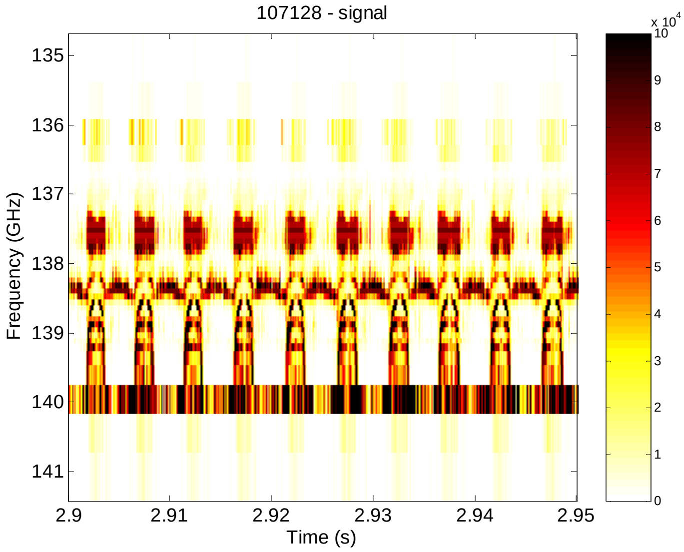

Figure 10. Measured spectra during passages of magnetic islands.

2.3.3 Overview of the CTS diagnostic at ASDEX Upgrade

F. Meo, H. Bindslev, S. B. Korsholm, V. Furtula, F. Leipold, F. Leuterer, P. K. Michelsen, D. Moseev, S. K. Nielsen, M. Salewski, M. Stejner, J. Stober*, G. Tardini*, D. Wagner*, and the ASDEX Upgrade team*
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The CTS diagnostic installed on ASDEX Upgrade uses the 1 MW dual frequency gyrotron as the probe. The 105 GHz mode is used where power levels up to 620 kW can be attained. The 105 GHz frequency mode is used as the probing radiation where power up to 620 kW for 10 seconds has been attained. Near back-scattered radiation is collected by neighboring electron cyclotron resonance heating (ECRH) antenna located in the same port. The CTS diagnostic at AUG uses the main portion of the ECRH #2 transmission line. The ECRH antennae are steerable enabling the possibility of different scattering geometries. The scattered radiation is transmitted to the CTS receiver in the HE11 mode via a 70 m corrugated waveguide to the free space propagation portion – the matching optics unit (MOU) box located in the gyrotron hall. Additional mirrors for the CTS transmission line are installed in the MOU box#2. One of the mirrors is movable and can intercept the incoming radiation between the universal polarizers and the phase correcting mirror permitting the polarization of the received radiation to be defined. The fixed mirror redirects the radiation to the CTS receiver. This system will make use of the very substantial investments at AUG in fast ion sources (Neutral Beam Injection and ICRH) and in new Mega-Watt power level gyrotrons, which are used as sources of the probing radiation in the CTS system. In addition to permitting fast ion dynamics to be studied in ITER relevant conditions, the AUG CTS system also provides experience with the use of high power gyrotrons in a CTS system, as would be required in a fast ion CTS diagnostic for ITER. Details of the commissioning can be found in Ref. [1]

1. F. Meo et al, Rev. Sci. Instrum. **79**, 10E501 (2008).

2.3.4 Final hardware commissioning of the CTS diagnostic at ASDEX Upgrade

F. Meo, H. Bindslev, S. B. Korsholm, V. Furtula, F. Leipold, F. Leuterer, P. K. Michelsen, D. Moseev, S. K. Nielsen, M. Salewski, M. Stejner, J. Stober*, G. Tardini*, D. Wagner*, P.P. Woskov**, and the ASDEX Upgrade team*
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The final hardware commissioning of the CTS diagnostic was successfully completed in early 2008. The original 22 resonator notch filters have been replaced by two filters of a redesigned 16 resonator version to improve the insertion loss over a broader bandwidth outside the filter rejection band (constructed and designed by General Atomics). As a result, the insertion loss for each filter is an impressive < 2 dB over a broader frequency range outside the notch ranging between 98 and 107 GHz. The original filters had a depth of about 60 dB and 200 MHz bandwidth. Stray radiation experiments on the Odyssey-2 gyrotron (performed in 2007) have concluded that the total attenuation should be > 100 dB to avoid gain compression of the IF amplifiers and to avoid potential damage to the mixer. In order to achieve this attenuation (> 50 dB each) with fewer resonators, the rejection bandwidth had to be set to a narrower 130 MHz width. The narrower bandwidth is still well within the frequency range of the gyrotron frequency operating excursion during steady state operation. The difference in notch depth can be clearly seen in Figure 11

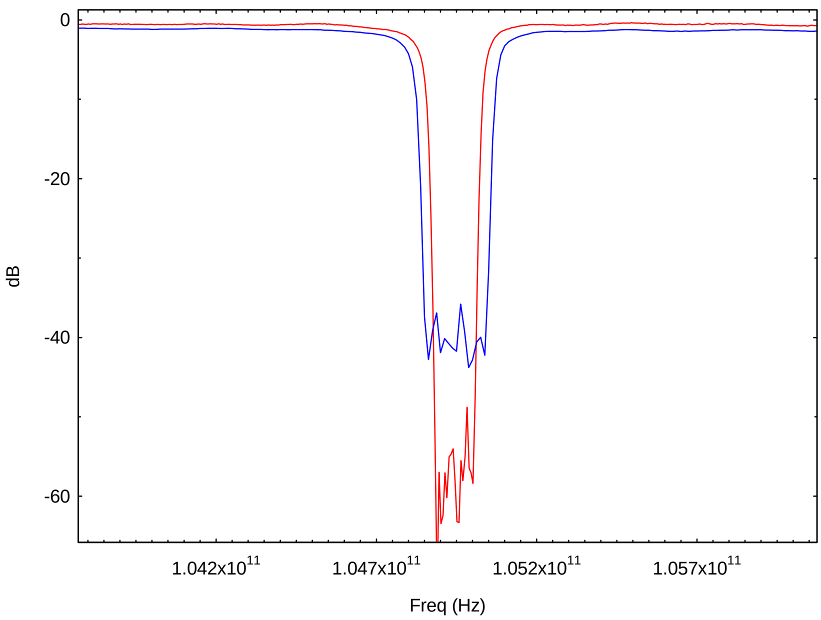

Figure 11. The attenuation curves for the new 16 cavity notch filters for a 200 (blue) and 130 (red) MHz width

In collaboration with IPP engineers and technicians, a detailed investigation of the vulnerability of in-vessel components to direct exposure of non-absorbed gyrotron radiation has been completed. An agreement was established for limited injection energy for every discharge. A new pulse generator card designed and made by Risø DTU has also been installed and successfully used to produce complex gyrotron triggering waveforms. This has enabled increased flexibility to perform different measurement windows during a discharge while remaining within the limited injection energy allowed. In addition, gyrotron in-vessel stray radiation measurements have been carried out to investigate the impact of non-absorbed radiation on the ECE diagnostic. Results have shown that for launch angles directed away from the ECE lens, the radiation is redistributed and is less than 5 μW at the lens. Therefore, the possibility of installing a voltage controlled attenuator, triggered by the gyrotron, can be installed on the ECE line. This will allow the possibility of using the ECE diagnostic during CTS experiments in the future.

2.3.5 Investigation of spurious signals

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Overlap scan experiments in near parallel scattering geometry have shown that the alignment agrees to within 1° between experiment and calculation. However, a major portion of CTS experiments in 2008 was dedicated to study the unexpected spurious signals that appear in the scattering data which were first seen in the experimental campaign of 2007. Dedicated experiments were carried out and identified some of the physics behind the spurious signals and to find a possible remedy. Two distinct types of spurious signal have been identified: The first type is assigned the name type A which exhibits a temporal erratic behaviour and has amplitudes of 2 – 3 orders of magnitude higher than the ECE background signal. Type A spurious signals exist only in H-mode and affect in the innermost channels (±500 MHz; close to the gyrotron frequency line). The second type, assigned the name type B, exhibits a more well-behaved temporal characteristic which can pose as overlap. This type of spurious signal exists only in Ohmic and L-mode plasmas and affects the whole spectrum. Theories on the cause need to be further investigated. Currently, there is a hypothesis that ECRH heating of ELM filaments cause type A spurious signal as shown in Figure 12. For type B spurious signals, the present hypothesis is ECE absorption and reemission of a broader L-mode/Ohmic plasma edge. A remedy discharge for type B has been found in L-mode and Ohmic plasmas whereby the plasma was shifted towards the inner column, and hence away from the ECRH antenna. This scenario can be used for CTS experiments in Ohmic and L-mode discharges. There is still no remedy (if any) found for type A in H-mode discharges. However, experiments have concluded that spurious signal type A does not jeopardise the capability of the CTS diagnostic to measure fast ions at different scattering geometries – at least for heating powers of up to 7 MW, which was the maximum power used in the experiments in the 2008 campaign. Filtering routines have been developed to remove some of the erratic behaviour of the type A spurious signal from the data.

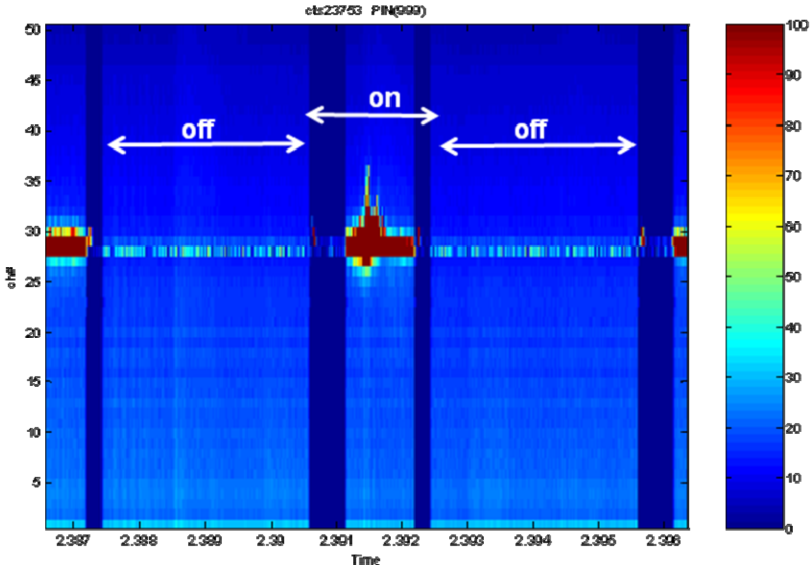

Figure 12. Contour of the raw signal (in eV) of the CTS signal of a discharge with no overlapping receiver and probe beams. The abscissa and ordinate represent the time and channel number (increasing with RF frequency) respectively. A worst scenario of the spurious type A can be seen in the data during the gyrotron-on period. In this example, it covers from -300 to +600 MHz from the gyrotron frequency line (channel 28).

2.3.6 Preliminary scattering results for the ASDEX Upgrade diagnostic

F. Meo, H. Bindslev, S. B. Korsholm, V. Furtula, F. Leipold, F. Leuterer, P. K. Michelsen, D. Moseev, S. K. Nielsen, M. Salewski, M. Stejner, J. Stober*, G. Tardini*, D. Wagner*, and the ASDEX Upgrade team*
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An example of CTS results is shown in Figure 13 for a near perpendicular scattering geometry in an AUG L-mode plasma with ion cyclotron heating (ICRH) (minority hydrogen, $R_{2\omega H} \approx$ center). The frequency range shown is between 105.4 and 106.5 GHz (gyrotron frequency = 104.95 GHz) which corresponds to approximately 2 – 20 keV for hydrogen. The plasma scenario for coupling ICRH power is still not optimized. However, the increasing stored energy (Wmhd) during the ICRH ramp-up phase suggests some heating is occurring until it decreases again – most probably due to the increase in impurities indicated by the increase in Prad. The CTS scattered spectrum in Figure 13 broadens during the ICRH ramp-up while the density and temperature remain nearly constant. Impurities such as tungsten and carbon, which are the main contributors to the Prad-signal, can distort the spectrum and can explain the broadening. However, scattering simulations have shown that due to the higher mass of the impurities, this should only occur for the portion of the spectrum below 0.4 GHz from the main gyrotron frequency. Therefore, the scattering at the higher frequency region is an indication of hydrogen heating from ICRH.

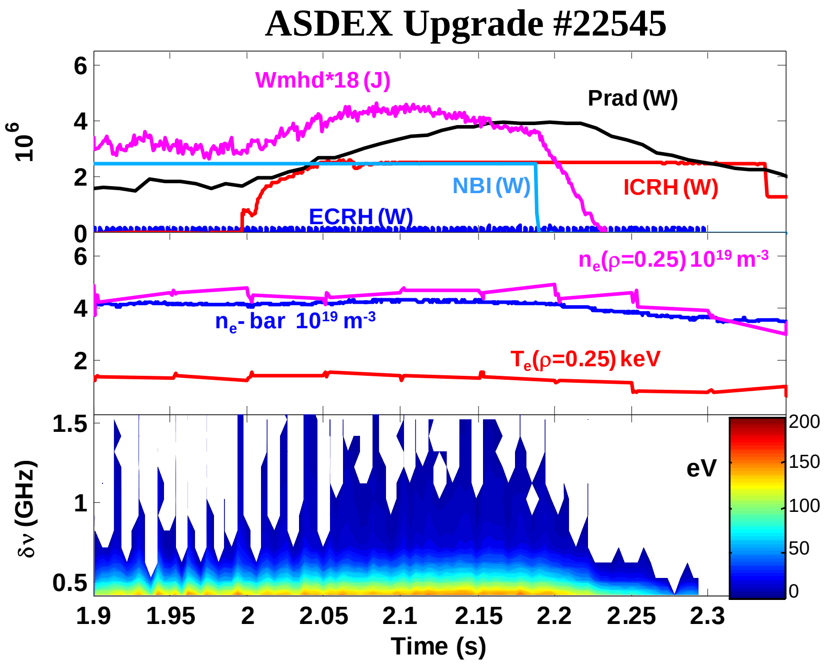

Figure 13. Time traces of an ICRH and neutral beam heated ASDEX Upgrade L-mode discharge. The top graph shows the traces of the ECRH, ICRH, total radiated power, NBI, and the stored energy from MHD scaled by 18. The middle graph shows the time trace of the core line integrated density from the interferometer and the density (blue) and temperature (red) at $\rho = 0.25$ from Thomson scattering. The bottom graph is the contour of the CTS spectrum for $\angle(k^{\delta}, B) \approx 100°$ and a scattering volume located at the plasma center. The high frequency portion of the scattered spectrum is plotted (+$\delta\nu$ 0.4 – 1.5 GHz) corresponding to the energy range for hydrogen of approximately 2 – 20 keV.

Preliminary scattering experiments were carried out at the end of the 2008 campaign to study fast ion physics for different NBI sources at two different pitch angles and scattering volume locations in a H-mode plasma. ASDEX Upgrade is equipped with a flexible NBI system with 8 sources – each at about 2.5 MW of power – providing a variety of pitch angles and injection energies. As a first step, comparison between the CTS scattered spectra and results from the transport simulation package at IPP Garching, TRANSP, will give new insight on the physics issues of fast ion transport. The NUBEAM module in TRANSP computes the time-dependent deposition and slowing down of the fast ions produced by NBI, taking into consideration beam geometry and composition, ion-neutral interactions (atomic physics), anomalous diffusion of fast ions, the effects of large scale instabilities, the effect of magnetic ripple, and finite Larmor radius effects. The simulated fast ion distribution from TRANSP – which is resolved in pitch angle and energy in a volume equivalent to the experiment's scattering volume – is projected onto the resolved fluctuation vector. This becomes the input for the scattering simulations. The graph in Figure 14 shows the comparison between two phases of the discharge with about 7 MW of beam heating (source 3 and 8) in blue and 2.5 MW of NBI power (beam source 8) in green. The injection energy of beam source 3 and 8 is 60 keV and 93 keV, respectively. The figure shows a good agreement in the amplitude and spectral shape. However, the simulations exhibit a broader bulk feature. The inference calculations to attain the fast ion distribution from the scattered spectra are currently in progress.

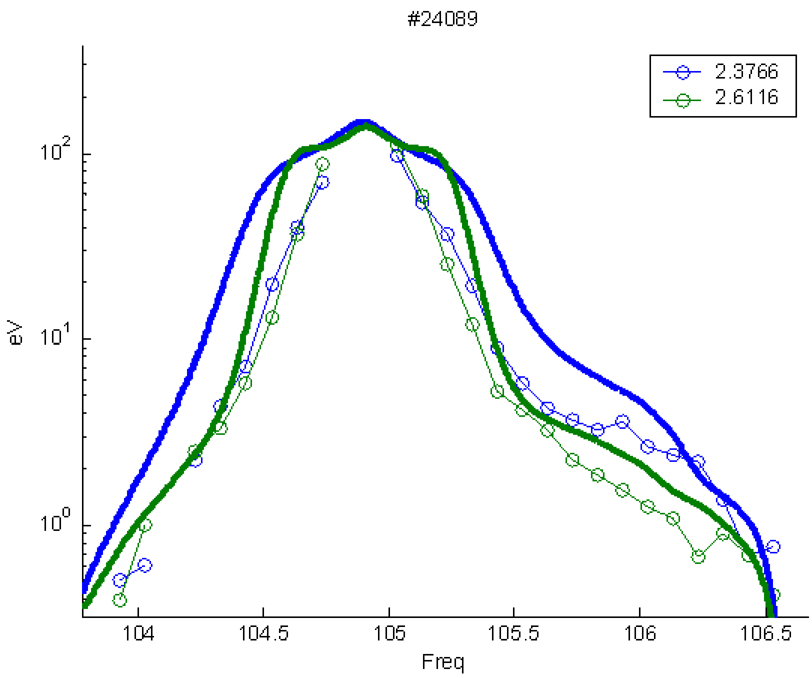

Figure 14. Scattering spectra for ASDEX Upgrade NBI heated discharge for two beams (in blue) and one beam (green). The curves with the open circles are the experiment and the simulated data are the thick lines.

2.3.7 Effect of mode activity in the plasma edge region on the ECE background in the ASDEX Upgrade CTS receiver.

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The fundamental and 2. harmonic electron cyclotron resonances corresponding to the 100-110 GHz frequency range spanned by the CTS receiver at AUG are - depending on the choice of toroidal magnetic field strength - located close to or in the plasma edge region. The effects of ELMs and other modes located near the plasma edge on the ECE radiation can therefore be studied by using the CTS receiver as a highly sensitive ECE radiometer when the 105 GHz gyrotron is turned off. This provides opportunities both for independent studies of modes in the plasma edge region and for correlating such mode activity with any effects seen in the scattered signal when the gyrotron is turned on. In this respect it should be noted that the spatial locations of the ECE resonances corresponding to the 50 channels of the AUG CTS receiver span regions which are approximately 10 centimetres wide on the high field side where the fundamental resonances are located, and 20 cm wide on the low field side where the 2. harmonic resonances are located. This corresponds to spatial resolutions of 0.2 cm and 0.4 cm on the high and low field sides respectively, while the time and energy resolution are 10 μs and 0.1 eV.

Preliminary studies of modes in the ECE background were conducted during the fall and winter of 2008 and lead to a number of important findings.

- A strong modulation of the ECE radiation across many channels can be clearly associated with ELMs – see Figure 15 (left) for an example. The build-up to an ELM is well resolved both spatially and with respect to time and energy. The final rapidly evolving part of the ELM instability is not well resolved in time, however.

- A strong temporal correlation between ELMs and part of the spurious signals in the scattered radiation has been established as discussed in subsection 2.3.5. The physical mechanism behind this is thought to be resonant heating of the expanding ELM filaments.
- By direct Fourier analysis of the ECE background several modes have been found with frequencies up to 50 kHz (the Nyquist frequency of the reciever) – see Figure 15 (right) for an example. Some of these mode chirp strongly in frequency and others display up to 6 harmonics. This last type is tentatively identified as the Edge Harmonic Oscillation described by Suttrop et al, PPCF, 45 (2003), 1339.

The nature of these background modes and the effects of ELMs on the ECE background continue to be a subject of interest for the CTS group both for the insight it affords in the spurious scattered signal and as an independent study of the edge region. Collaboration with the plasma turbulence group at Risø DTU on numerical studies of the ECE radiation during an ELM is also under consideration. The plasma turbulence group at Risø DTU has great expertise in numerical studies of the edge region and has already made significant contributions toward understanding the signal from Langmuir probes during ELMs (see, e.g. [1]). The results from such collaboration could provide important insight in the effect of ELMs for the CTS diagnostic and would be of general interest for the wider plasma physics community.

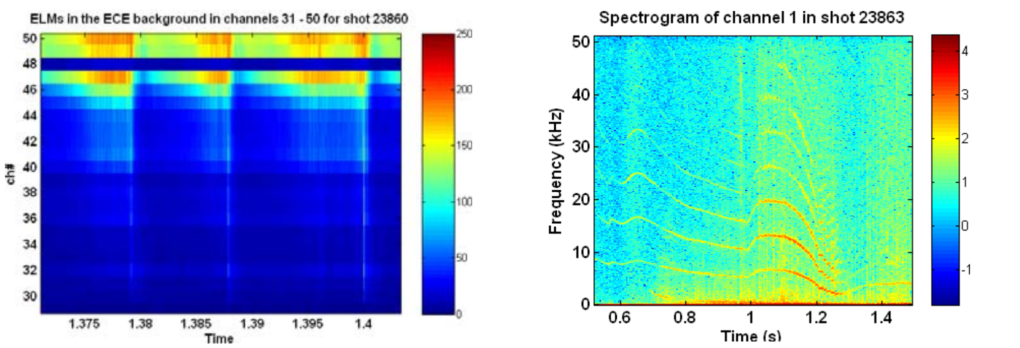

Figure 15. Left: ECE radiation in channels 31-50 for a time period in shot 23860 when the gyrotron was turned off. 3 ELMs clearly modulate the spectrum during this time. Note that channel 48 was bypassed and used for other purposes in this measurement. The colour scale is linear and in eV. Right: a spectrogram for channel 1 in shot 23863 during a time period when the gyrotron was turned off. A mode and 6 harmonics can be clearly seen. The colour scale is logarithmic.

1. O.E. Garcia et al. Plasma Phys. Control. Fusion **48,** L1-L10 (2006).

2.3.8 Improvements of the ASDEX Upgrade CTS receiver

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During the shutdown of ASDEX Upgrade (winter 2008/09) the CTS receiver was taken to Risø DTU in order to characterise and improve the equipment. In Figure 16, a block diagram of the improved receiver is shown. All components have been individually characterized. The following modifications and improvements on the receiver were made:

- The local oscillator has been tuned to 96.43 GHz in order to center the gyrotron frequency in the filter bank (the gyrotron frequency had been changed after the initial procurement of the CTS mixing stage).
- A wide band amplifier has been installed after the mixer.
- The mixer, LO and wide band amplifier were built in a copper box in order to shield against electromagnetic radiation.
- The triplexer has been replaced by a 4-way power divider with subsequent band pass filters to improve the isolation between the three branches.
- A power divider has been inserted between the 2nd and 3rd amplifier stage. The signal is used for monitoring purposes.
- The components from the 4 way power divider to the 3rd stage amplifiers were mounted in a copper box, where the branches are electromagnetically shielded to each other and to electromagnetic noise in the surroundings. This unit is referred to as the "Active triplexer unit".
- The band pass filters in the low frequency and high frequency band are protected by additional filters as they did not provide adequate rejection over the whole frequency band.
- The detector diodes have been individually characterized in order to allow a more precise measurement taking the nonlinearity into account.

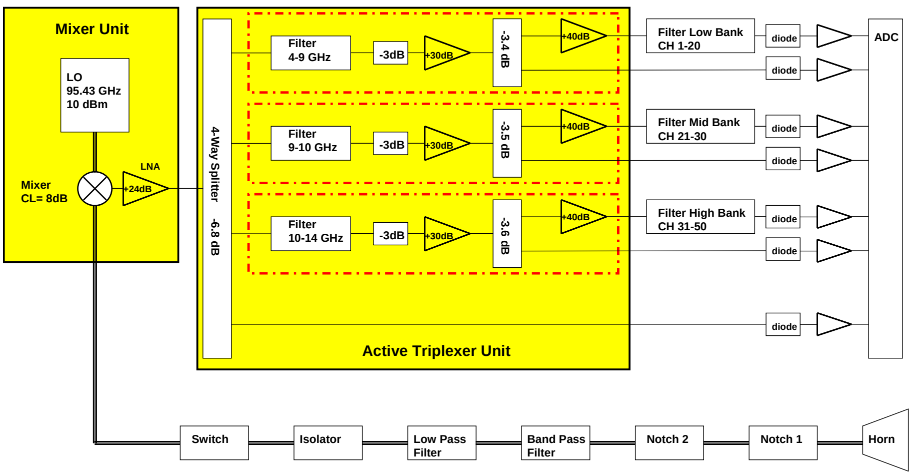

Figure 16. Block diagram of the improved CTS receiver

The RF unit

The RF unit has been measured with a variable microwave source and a spectrum analyzer behind the switch. The blue dots in Figure 17 show the measurements of the transmission in arbitrary units. Between 80 GHz and 95 GHz, the measured transmission was below -65 on the arbitrary scale in Figure 17 and has not been recorded. The transmission in the frequency interval between 97 GHz and 104 GHz was between -45 and -40 on the arbitrary scale. Above 110 GHz, the transmission was below -65. The blue, green and red bar indicate the frequency range projected the low mid and high band in the IF stage. The yellow range (USB) indicates the sensitivity of the filter banks behind the active triplexer. When mixing frequency, a mirror image can also be seen in the IF stage (LSB). The band pass filter in the RF line does not permit frequencies below 95 GHz to pass. The dip at 105 GHz is caused by the notch filters.

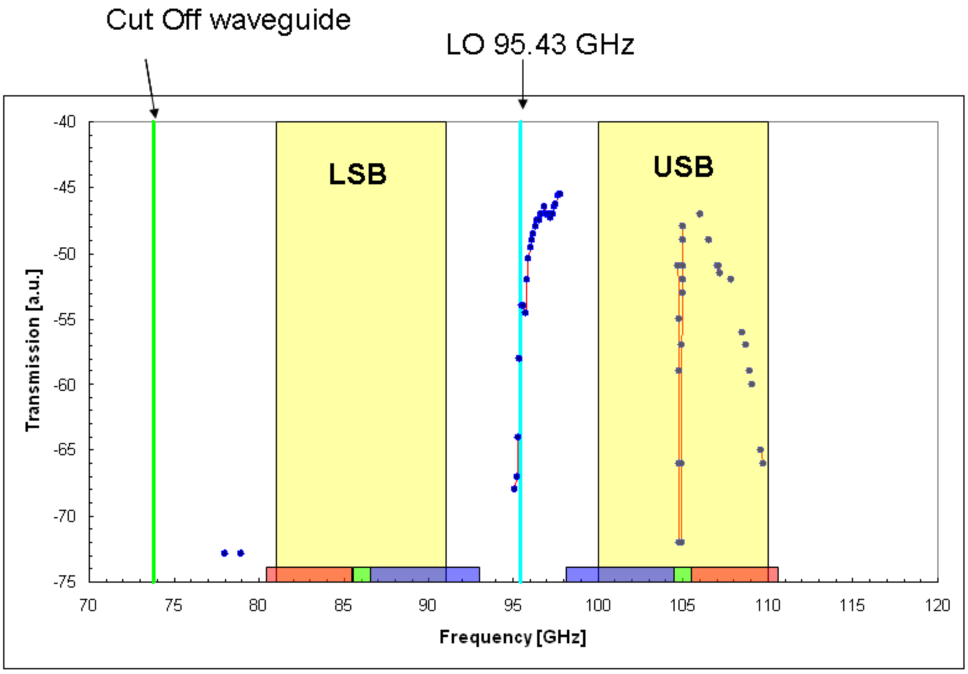

Figure 17: Frequency chart. (see the explanation in the text above)

The mixer unit

The mixer is used to convert the CTS signal down to a frequency range between 4 and 16 GHz. The gyrotron frequency was found to be 104.93 GHz. In order to project the gyrotron frequency to the mid frequency (9.5 GHz) in the mid band (9-10 GHz), the local oscillator frequency should be at 95.43 GHz. A wide band amplifier (Mini-circuits) with a bandwidth from 700 MHz to 18 GHz has been attached directly to the mixer. Figure 18 shows a photo of the mixer, LO and wide band amplifier mounted in a copper box. This unit is referred to as “the Mixer Unit”.

Figure 18: The mixer unit in its new enclosure

The triplexer

The triplexer installed in the system had the advantage to split the power in different frequency bands with a minimum of losses. However, a drawback was measured. The isolation between the three output ports of the triplexer was low. This means that a reflection of a signal at an output port due to an improper termination can cause forwarding of this signal to another output port causing “ghost” signals. Therefore the triplexer has been replaced by a 4-way power splitter with subsequent filters. Since an additional amplifier has newly been installed, the insertion loss of approximately -7 dB is not severe. In order to ensure a proper isolation between the branches, the filters and amplifiers for one band is mounted in an electromagnetically shielded pocket within the triplexer unit. The unit consisting of power splitter, filters and 2 stage amplifiers is referred to as “active triplexer. Figure 19 shows the characteristic of the active triplexer.

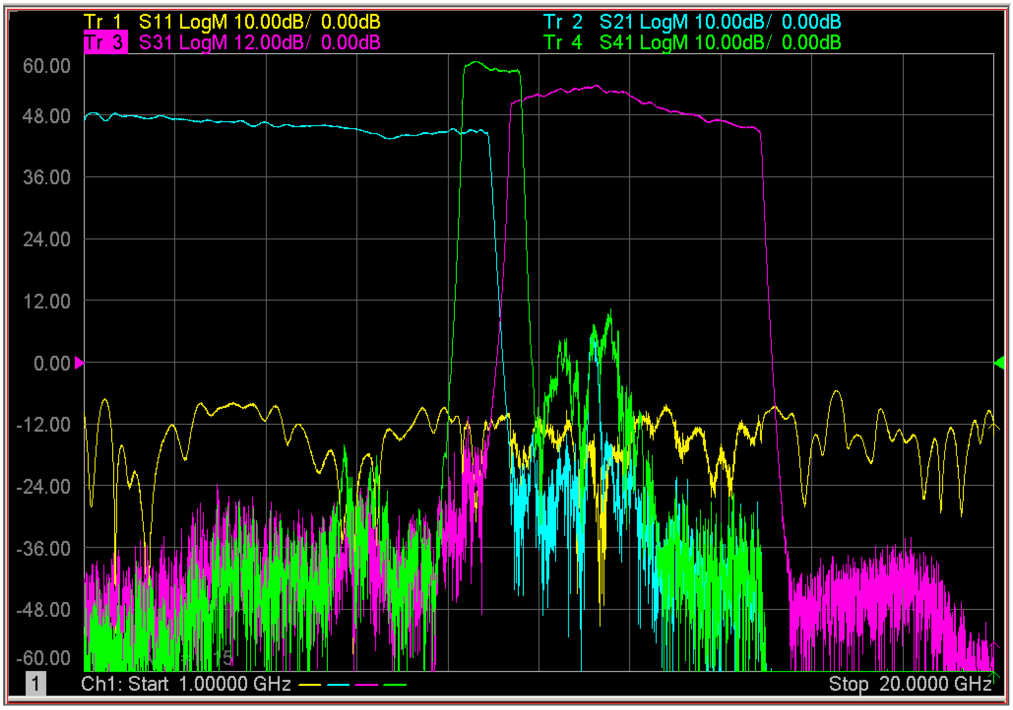

Figure 19: Characteristic of the triplexer: Transmission of the low frequency band (blue), mid frequency band (green) and the high frequency band (magenta). The horizontal axis corresponds to a frequency from 1 GHz to 20 GHz. The input power was -40 dBm.

The filter bank

A filter bank is connected to each branch of the active triplexer. The filter bank splits the signal into a number of frequency ranges with a width generally of 100 MHz, but up to 1 GHz. Each filter is connected to a detector diode. The voltage at the diode represents the signal within the frequency range of the given filter. Figure 20 shows a selected number of filters in the high frequency filter bank (100 GHz to 14.5 GHz). In this example there are 4 filters with a width of 100 MHz (narrow band filters) and 1 filter with a width of 1 GHz (wide band filter). As can be seen from Figure 20, the narrow band filters work fine in a frequency range between 10 and 14 GHz. However, at frequencies above 14 GHz, some filters have a transmission window. This means that a filter, designed for a frequency range from 11.0 to 11.1 GHz responds also to a signal with a frequency of 14.3 GHz or above causing ghost signals. This problem has been solved during the past campaigns by placing a low pass at 14 GHz filter in front of the whole filter bank, on the expenses of a partly cut off of one filter. In order to overcome this problem in the future, additional filters have been inserted in front of individual filters or groups of filters to ensure a rejection of all non-desired frequencies. Figure 21 shows the characteristic of the improved filter bank

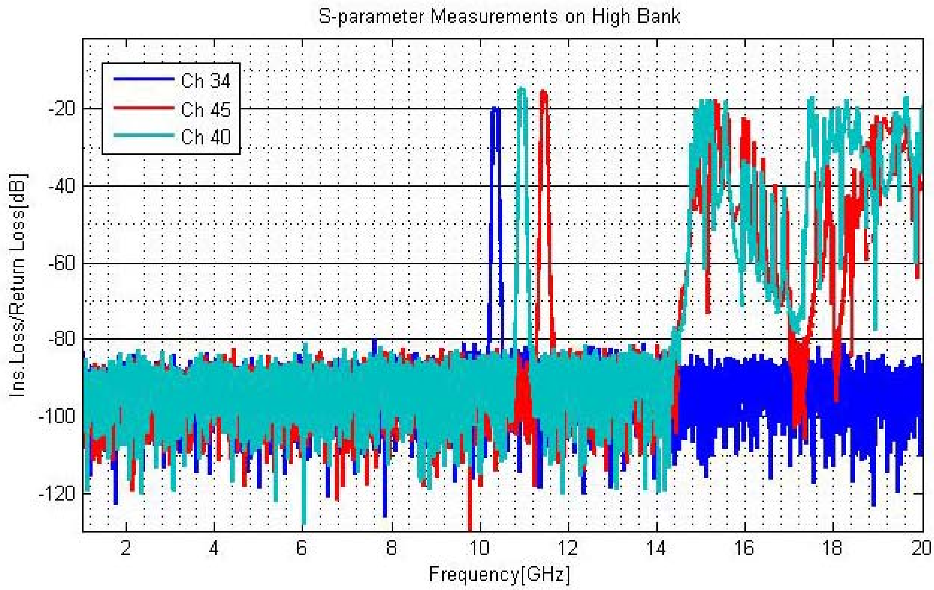

Figure 20. Selected filters from the high frequency band and their transmission windows (without the low pass filter used during the campaigns).

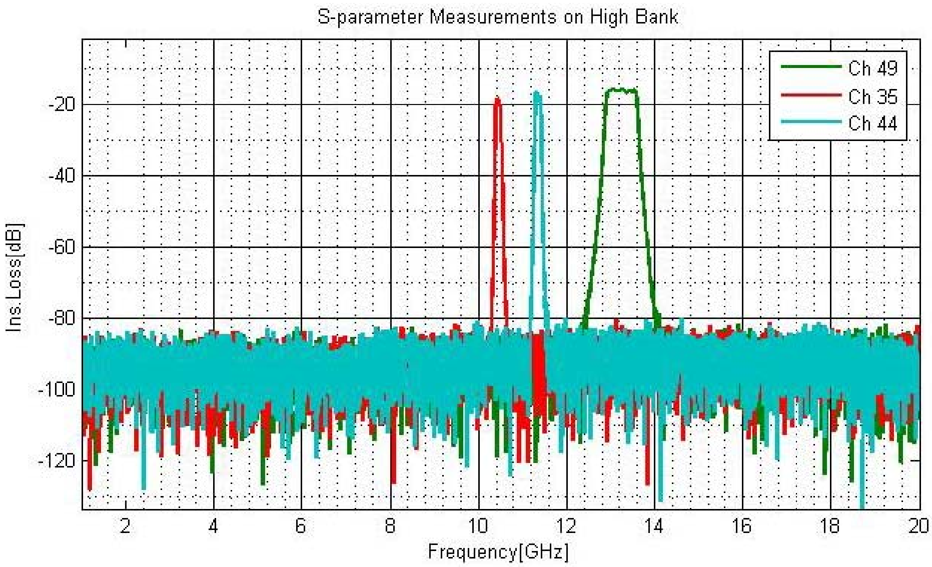

Figure 21. Filter transmission in new configuration

Detector diodes

The detector diodes convert the intensity of the IF signal into a DC voltage. In a first approximation, the characteristic of the diodes can be assumed linear, when the power range used is small. The characteristic is also frequency dependent. Figure 22 shows the characteristic of two diodes at a frequency of 5 and 14 GHz. The characteristic of all individual diodes have been measured for a range of relevant frequencies and the range of relevant powers. This allows improvement of the calibration by taking into account this power and frequency dependence of each channel.

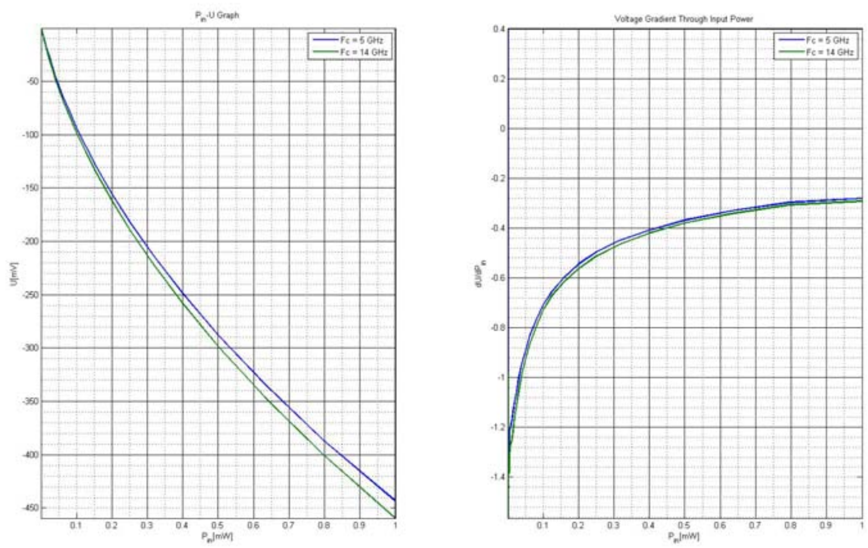

Figure 22. Characteristics of the negative biased detector diodes measured at 5GHz and 14 GHz. Left: the output voltage as a function of input power (0 to 1 mW), Right: the gradient of the output voltage as a function of input power.

2.3.9 The fast ion CTS diagnostic for ITER

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Since the ITER CTS feasibility study of 2003 [1], a continual effort at Risø DTU has been made to mature the design of a fast ion CTS diagnostic for ITER. As described in Ref. [1], the proposed fast ion diagnostic comprises of two parts, a receiving antenna located on the high field side (HFS) behind the blanket modules, and a receiving antenna on the low field side (LFS) in equatorial port plug #12. Each antenna views the scattered light from two dedicated 60 GHz 1 MW gyrotron sources. With the proposed system it is possible to resolve the dynamics of confined fast ions (including fusion born alphas) in the direction nearly perpendicular to the magnetic field (LFS antenna) and in the direction nearly parallel to the magnetic field (HFS antenna), within the ITER measurement requirements. Due to the spatial constraints, the HFS antenna is the most challenging part of the diagnostic, and much emphasis has been put on obtaining a good solution for that part of the system. It should be noted that the HFS antenna will give information on dynamics of fast ions on passing orbits, and as a spin-off it will also give the toroidal bulk ion rotation velocity.

The CTS diagnostic was not sufficiently matured at the time of the 2001 ITER baseline design, and therefore CTS has been carried as a so-called un-credited diagnostic. With the maturity of the diagnostic based on the results and experiences on TEXTOR and ASDEX Upgrade, and the progress of the ITER CTS design at Risø DTU, the ITER diagnostic working group decided - as part of the design review - to include the LFS part of the fast ion CTS diagnostic in the new ITER baseline design.

An EFDA contract with the task title: "Support of diagnostic design for ITER" concerns an engineering design of the ITER Collective Thomson Scattering diagnostic and was obtained in 2007 and finished during 2008 [1]. The main part of the work was described in the yearly report [2]. The main subjects are described in the following sections.

1. ITER CTS reports by Risø DTU. Please find via http://cts.risoe.dk
2. Association Euratom – Risø National Laboratory Annual Progress Report 2007

2.3.10 Comprehensive outline plan for the full development of the CTS diagnostic for ITER

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This work comprises a proposal for a comprehensive outline plan towards the full development. Besides a presentation of the outline plan, an overview of key R&D tasks on critical components is also included. The outline plan is divided in two – one covering the LFS (near perpendicular viewing) part, the other covering the HFS (near parallel viewing) part of the diagnostic system. The main part of the plan for the system (not including approvals and QA) is:

- Detailed design of all components; mirrors, waveguides and transmission lines for both the measuring system and for the gyrotron
- Design of mountings for mirrors and waveguides
- Resolving integration issues in equatorial port plug 12 (iterative)

- Neutronics and thermal stress calculations of the full CTS system and surroundings
- Mockup of all CTS related structures in the equatorial port plug #12
- Specification and procurement of gyrotron
- Specification of receiver electronics and data acquisition hardware
- Creation of receiver test model and procurement of receivers and other components
- Building whole system

2.3.11 Engineering design of the front-end quasi-optical components for the HFS antenna system

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The HFS receiver system consists of a mirror assembly and a receiver horn antenna consisting of 10 individual horns. The four mirror assembly transforms the astigmatic anisotropic Gaussian beam (approximate size: 100 mm x 10 mm) coming from the plasma to an isotropic Gaussian beam with a beam waist of 4.5 mm corresponding to a divergence angle of 20.3˚, which is accepted by an antenna horn. In order to verify the proper operation of the receiver system, which was modelled in MatLab and designed in CATIA, a 1:1 mock-up has been built; initially only with one antenna horn. The mock-up consists of the HFS receiver antenna system and relevant parts of the involved blanket modules. The verification of the beam propagation is accomplished by feeding the antenna horn with mm-waves from a Gunn diode (60 GHz) and tracking the beam shape backwards. The beam is guided through the quasi-optical transmission line and detected by a detector diode mounted on a two-dimensional translation stage. The four mirror antenna system is shown in Figure 23.

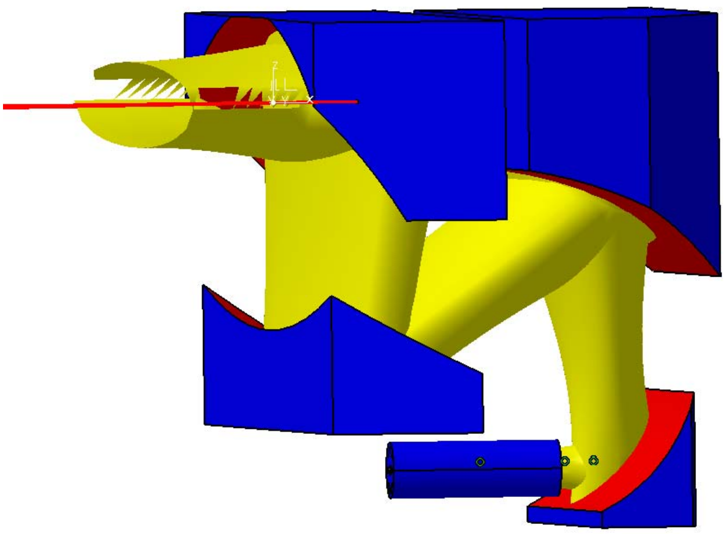

Figure 23: 3D picture from CATIA of the HFS receiver antenna.

2.3.12 Neutronics and Thermo-Elastic Modelling of the First Mirror of the HFS CTS system

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The first mirror of the high field side (HFS) collective Thomson scattering (CTS) system has a direct line of sight to the plasma and is exposed to severe neutron and photon fluxes. These are further enhanced by the necessity to cut out shielding blanket material due to space limitations on the inboard side (HFS) of the tokamak: There is not enough room to place the receiver behind a blanket of nominal thickness. These thermal loads result in strains in the mirror. The present modelling of neutronics and thermo-elastic stresses indicates that the mirror curvature may warp. This may alter the beam quality, and therefore thermal effects have to be accounted for in the design of the mirror. Various mirror designs are being compared in terms of temperature distribution, the displacement, and thermal strain (after the von Mises failure hypothesis).

The modelling of neutron and γ fluxes is being performed by Monte Carlo simulations with the MCNP-5 code [2] assuming a plasma with 500 MW fusion power. In addition to neutrons, radiation from the plasma mostly in the VUV, UV, and x-ray ranges hits the first mirror. Various cooling systems are considered, as for example passive cooling, drilled internal channels or cooling channels which are welded on the back, optionally facilitated by cooling channels in the mirror. The mirror is assumed to be supported on the back side, allowing for free thermal expansion. The mirror material is assumed to be stainless steel.

There are several main conclusions of the present study [2] A guiding principle for designing CTS first mirrors is the need to minimize the use of material. Firstly, the mirrors should be thin (~10 mm) to avoid large thermal stresses. Thick mirrors were previously considered to reduce the neutron streaming through the weakened shielding due to the required additional cut-outs. However, the function of absorbing neutrons to protect the superconducting magnets should preferably be separated from the function of reflecting radiation for diagnostic purposes. The enhanced neutron streaming behind the mirror could be counteracted by a separate neutron absorber if necessary. The lower bound on the mirror thickness is given by thermal footprints of backside features for excessively thin mirrors and by the difficulty to manufacture large mirrors with the given reflecting surfaces. Secondly, the mirror geometry should preferably resemble the beam shape from a thermo-mechanical point of view. As the beam pattern is elliptical in shape, the mirror will as well be as close to elliptical shape as possible (though there are constraints). For example, the corners can be rounded. Though mirrors with corners are easier to manufacture, the material in the corners serves no function and unnecessarily adds to the cooling demand. Thirdly, another example is the support arm of the mirror for which it was found that a hollow holder is advantageous since bending resistance is mostly offered by the outer radii of the holder (with larger second moments of area) whereas the entire holder is approximately uniformly heated by volumetric heating. Material at the centre has therefore less bending resistance per unit heating power and should be avoided, and hollow holders are therefore beneficial. Lastly, it was further shown that it may be necessary to apply active cooling to maintain thermal stresses at an acceptable level and that at key positions sharp edges have to avoided due to thermal stress reduction.

Future work will include a detailed material selection with comparisons of various materials. The material has large impacts on temperature (e.g. via emissivities) and mirror displacement and is a high priority. Various cooling system options will be considered. Additional work will be dedicated to modelling of the reflection of millimetre waves from the thermally deformed mirror as the beam quality may deteriorate. Lastly, design improvements are foreseen for stress reduction purposes.

1. Tech. Rep. LA-UR-03-1987, Los Alamos National Laboratory (2003).

2. M. Salewski et al. Rev. Sci. Instrum.**79**, 10E729 (2008).

2.3.13 Engineering design of the front-end quasi-optical components for the LFS system

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The probing beams for the HFS and LFS CTS parts are launched via the equatorial port #12 on ITER. The LFS CTS receiver is also located in the equatorial port #12. The probing radiation for the LFS CTS system is provided from a gyrotron and fed by a corrugated waveguide into the equatorial port plug #12. The beam leaves the corrugated waveguide and propagates quasi-optically. The beam characteristic is a circularly symmetric Gaussian beam. The beam shape in the plasma has been calculated in the conceptual design [1]. In general, it is an anisotropic Gaussian beam. In order to perform this transformation in the receiver antenna system effectively two mirrors are required. The shapes of these two mirrors are calculated in Matlab. The mirror shape is imported into CATIA V5, where the mirror design is performed.

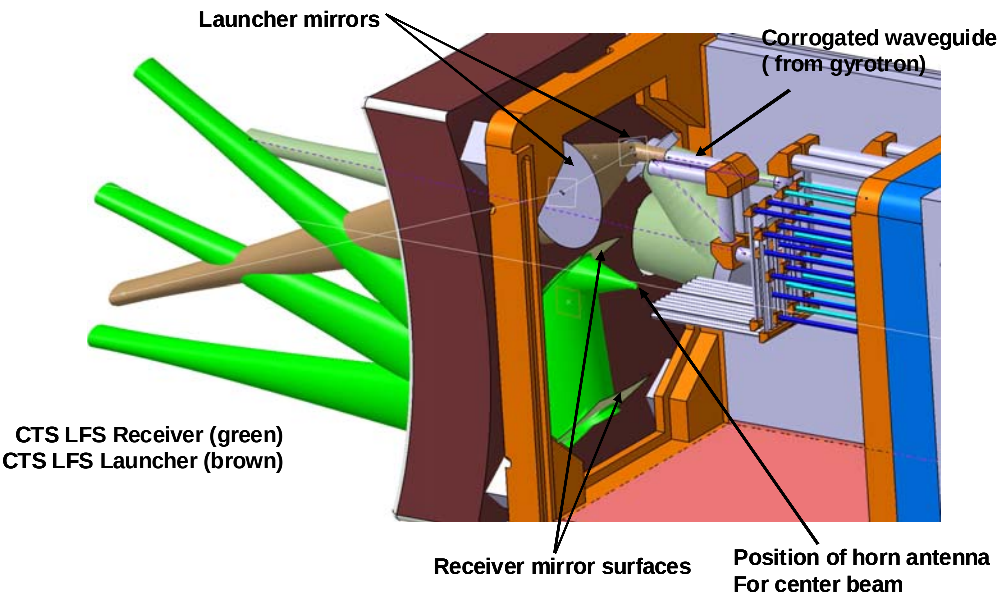

Figure 24: Equatorial port #12 on ITER with LFS CTS launcher and receiver beams, rear view.

Scattered radiation from the different scattering volumes is captured using the same pair of mirrors. This leads to highly astigmatic beams from the extreme positions, which have an angle of +/- 15˚ with respect to the centre beam. The receiver beams are shown in green in Figure 24. The beams from the extreme positions are only shown up to the first mirror.

Due to the highly astigmatic beam pattern for the beams deviating from the centre beam, another approach is performed. This approach contains only one mirror. The disadvantage of this approach is the huge required mirror, the advantage is, that the beams, even for the extreme beams have at least so small dimensions inside the port, that there is no overlap between two neighbouring spatial channels. The varieties of horns, which can detect these beams, still need to be investigated. Figure 25 shows a CATIA sketch of the mirror and the beam shapes.

1. "ITER Fast ion Collective Thomson Scattering – Feasibility study and conceptual design" H. Bindslev et al. (Association Euratom-Risø, Roskilde Denmark) Final Report of EFDA Contract 01-654, November 2003

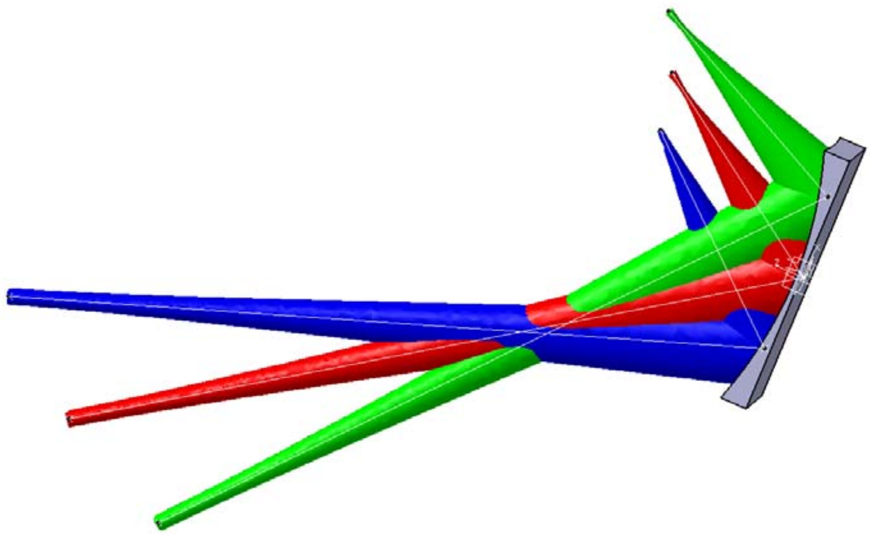

Figure 25: Sketch of the LFS receiver beams for a one mirror solution

2.3.14 Neutronics Calculations for the Collective Thomson Scattering Diagnostic System for ITER (Outboard)

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The proposed Collective Thomson Scattering (CTS) diagnostic system for ITER is exposed to intense neutron and gamma radiation, which is of concern both with respect to the heat loads on the quasi-optical receiving mirrors affecting their optical properties (Figure 26, M1 and M2), and with respect to the neutron fluxes streaming through the waveguides. Detailed neutronics calculations have been performed on the heat dissipation in the mirrors using the MCNP5 code with a 40 degree geometry input model [1].

The heat load to the mirrors provides a basis for estimating the thermal distortions of the mirror system impairing the microwave transmission properties. The calculations show that the mirror M2, which is exposed to primary (14 MeV) neutrons, has a non-uniform heat distribution with a 25% higher heat load on the front facing the plasma, while the heat distribution in mirror M1, which is shielded from direct neutron irradiation, is almost uniform.

1. M. Salewski et al., Rev. Sci. Instrum.**79**, 10E729 (2008).

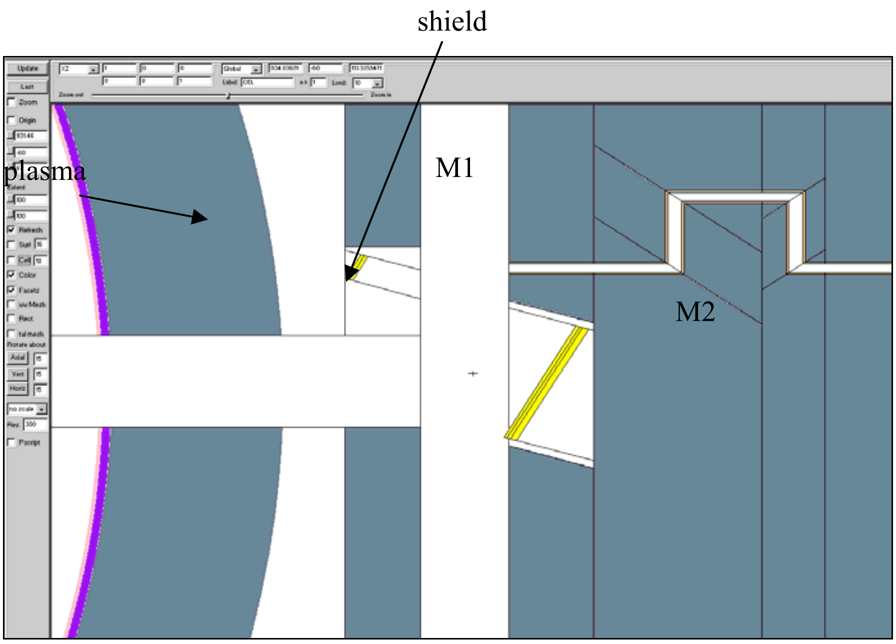

Figure 26. Vertical view of the position of the mirrors M1 and M2 for the CTS-system in the outboard plug.

2.3.15 Calibration methods

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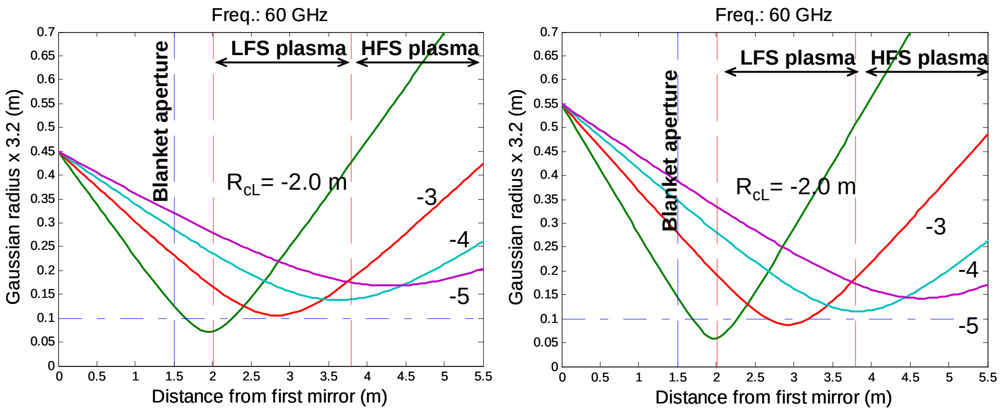
A calibration source should produce a known emission that covers the entire collection optics. Calibrating the front end is essential to monitor the changes in throughput from possible misalignments due to thermal expansions and disruptions. A prototype of such a source is being developed for the ECE diagnostic on ITER [1]. The material of choice is silicon carbide (SiC) and tests are being carried out by the University of Texas group. Preliminary results of the source have shown flat temperature profile between 100 – 800 GHz [2]. However, the data is noisy for frequencies below 100 GHz due to the limitations of the Michelson measurements. A dialogue between the University of Texas group and Risø DTU has started to extend the tests down to 55 GHz.

As in the ECE diagnostic, the source will not be in direct line sight of the plasma, but will be located behind the blanket module. The first CTS mirror for the LFS-BS system is just behind the blanket module about 1 m distance from the blanket's plasma facing surface.

Hence accommodating the calibration source will imply a larger distance between the plasma and the first mirror. The beam diameters for a first mirror displaced to 1.5 meters from the blanket edge are displayed in Figure 27 for a beam diameter of 0.45 m (a) and 0.55 m (b) at the first mirror. The vertical beam dimensions at the scattering volume for the LFS system will have a direct impact on the CTS signal, and hence affect the diagnostic measurement requirement. Hence to reduce the vertical beam dimension in the plasma will require further enlarging the beams sizes at the first mirror. Figure 28 shows the most promising design for the LFS front end. The figures shown in green are the dimensions required for full coverage of the source need to cover the optics. Hence displacing the entire optics about 0.5 m further away, would require increasing the mirror size by about 300 mm to 750 mm.



(a) (b)

Figure 27 Beam diameters (Gaussian radius × 3.2) as functions of distance from front-end mirror for the mirrors at 1.5 meters further inward.

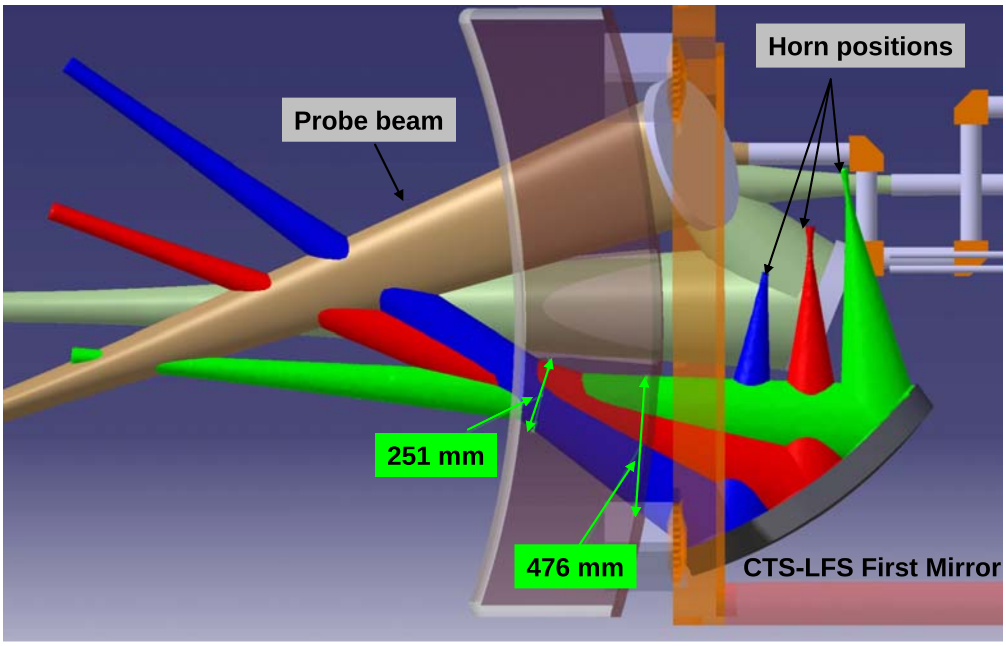


Figure 28. Side view of the CTS LFS front end installed in the equatorial port plug. The blanket module and the port plate are made semi transparent. The probe beam is in brown. Three of the ten receiver beams are shown by the blue, red and green those correspond to the upper most, middle and lower most extreme angle where their scattering volumes cover the entire LFS of the plasma.

1. M.E. Austin, P.E. Phillips, W.L. Rowan, R.F. Ellis, A.E. Hubbard, Review ITER ECE system

2. P.E. Phillips, M. E. Austin, W. L. Rowan, 17th Topical conference on High Temperature Plasma Diagnostics, Albuquerque, New Mexico, May 11 – 15, 2008

2.3.16 Design and manufacture of a corrugated horn antenna for the ITER CTS HFS mock-up

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A corrugated horn antenna has been successfully employed in the HFS CTS mirror system mockup for ITER. Calculations of the circular horn antennas employing empirical formulas have been performed. It could be shown, that the predicted beam shape matches with the measured beam shape. Another approach is made by using finite elements to calculate electrical fields inside the horn antenna. This approach can be relevant, when non symmetric antennas are used. See the left lower panel of Figure 29.

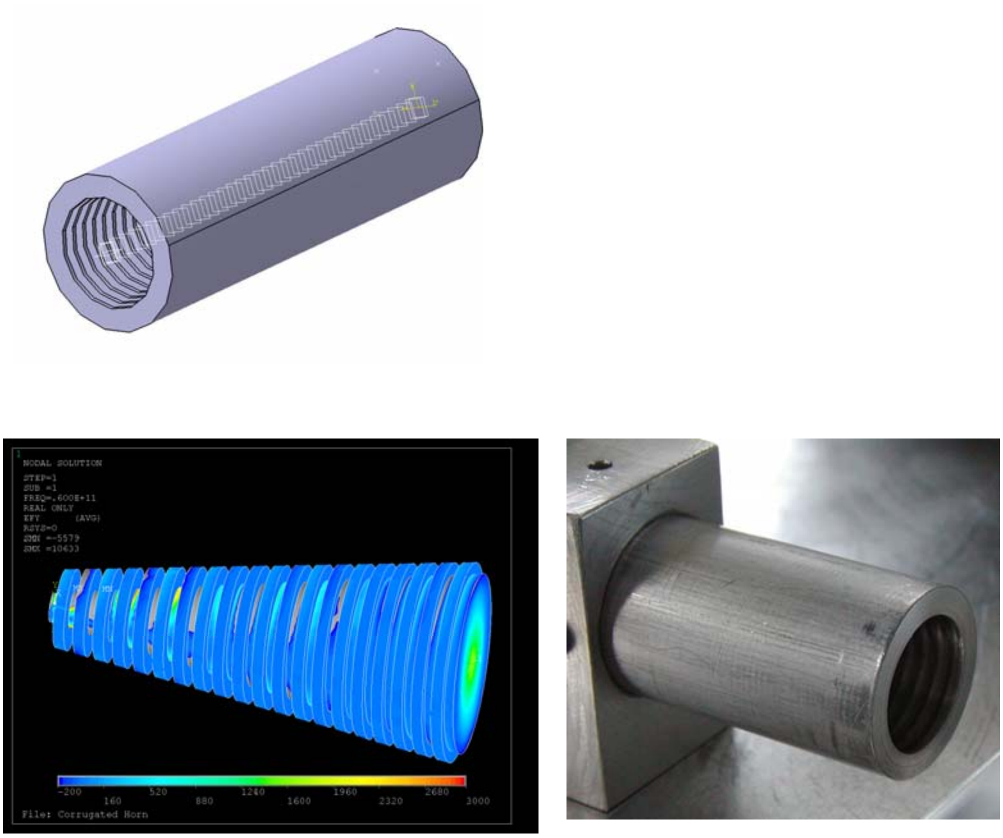


Figure 29. Circularly corrugated horn antenna for 60 GHz (left upper: CATIA drawing; right lower: Photo; left lower: space inside the horn in ANSYS

A TE11 mode is applied as a source. Figure 30 left shows the intensity of the total electrical field vector. Figure 30 right shows the magnitude of the vertical component of the electrical field at the opening of the horn antenna. A detailed evaluation of the data is still pending, but the contour plot suggests that a circular Gaussian beam can be expected. The reflection at the input was found to be -14 dB.

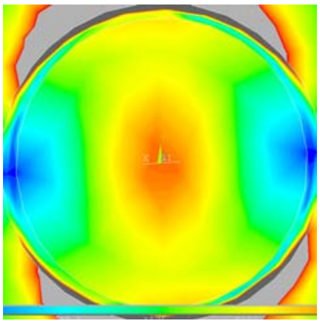
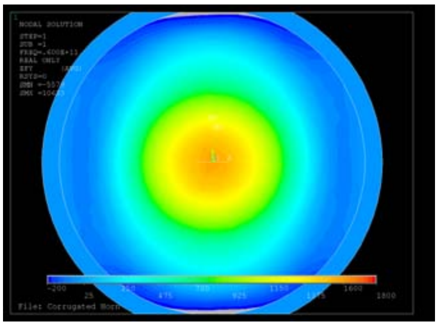


Figure 30. The total electrical field at the horn input (TE11 mode)



The vertical component of the electrical field at the horn opening

2.3.17 Notch filter design

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Recently, Risø DTU has invested in an effort to design and produce notch filters in order to build up the competence that will be highly desirable for the construction of the future CTS diagnostic systems – in particular the ITER CTS system.

The V-band (50-75 GHz) covers the expected frequency range for the ITER CTS system, but it was decided to make tests in the ku-band (12-18 GHz) which can be measured by the Risø DTU CTS group's vector network analyzer (VNA). The VNA is a coherent measurement device and is suitable for characterizing passive and active RF components where the output is the S-parameters. A two port device has output of 4 S-parameters, namely S_{11}, S_{21}, S_{12}, S_{22}. The parameter S_{11} represents return loss at port 1 while S_{21} represents insertion loss from port 1 towards port 2. For a passive device we have $S_{21}=S_{12}$ and S_{11}~S_{22}. The S-parameters are usually normalized to the input impedance found on each individual port. The notch filter waveguide is connected to waveguide SMA adaptors with the impedance on both ports of 50 Ω. The SMA adaptor is not part of the notch filter design.

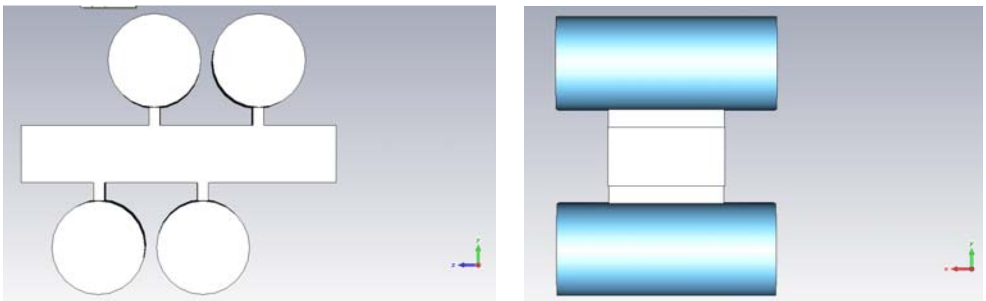

Figure 31. Top view and side view of a 4 cavity notch filter

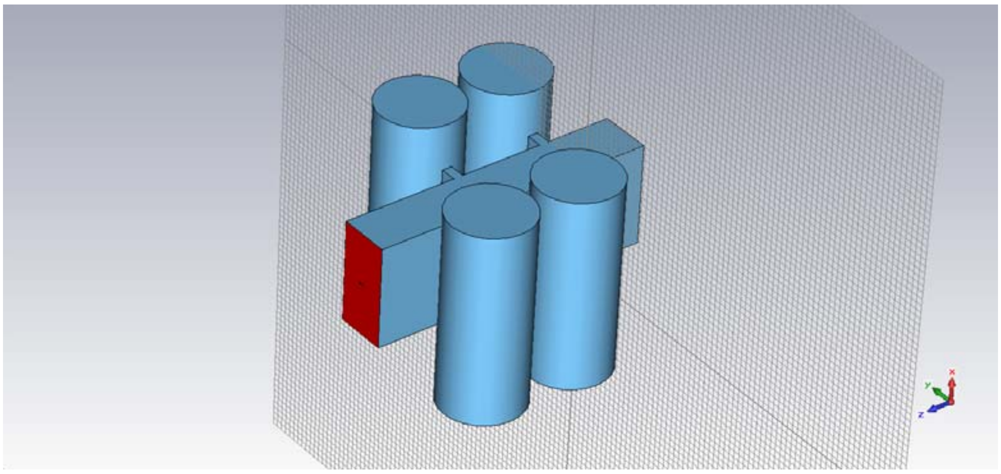

Figure 32. The 4 cavity notch filters in free view. The red surface shows the waveguide port that is connected to the SMA adaptor.

The notch filter has been simulated in *CST Microwave Studio*. The model is shown in Figure 31 and in Figure 32. When simulating the filter structure it turns out that the simulation time is quite long when the resonators are spaced very close in frequency spectrum. This is due to the fact that the solver is based on the *time domain solutions*. In our case we are seeking for a bandwidth of 100-200 MHz which is quite time consuming to simulate. Therefore, an important task is to produce a notch filter which can be tuned to the correct reject frequency if the bandwidth is larger than it is supposed to be. After the filter is machined the reject bandwidth can be tuned to the required value.

Figure 33 shows the simulated S-parameters and Figure 34 shows the measured ones. Notice the very deep notch of almost 80 dB and the width of 100 MHz. Also notice the two notches in the return loss just beside the notch. This is also what is predicted in the CST simulations. The return loss is somewhat higher then simulated, but this is mainly due to the non-perfect waveguide-to-SMA adaptors. In Figure 34 is also shown a photo of the produced notch filter.

The results achieved are quite satisfactory and the next step is to produce a waveguide notch filter operating around 60 GHz, which is required for the ITER CTS receiver.

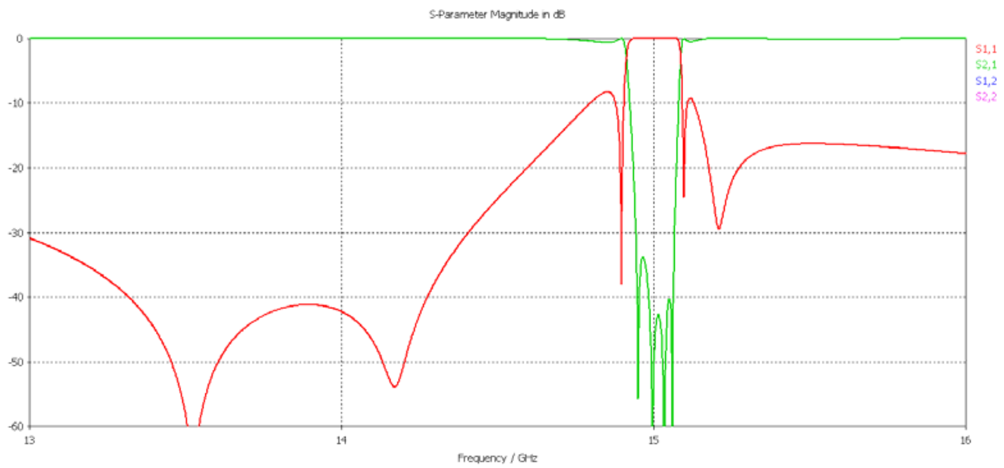

Figure 33 The simulated S-parameters of a 4 cavity notch filter in free view. The red curve shows the return loss while the green one presents the notch.

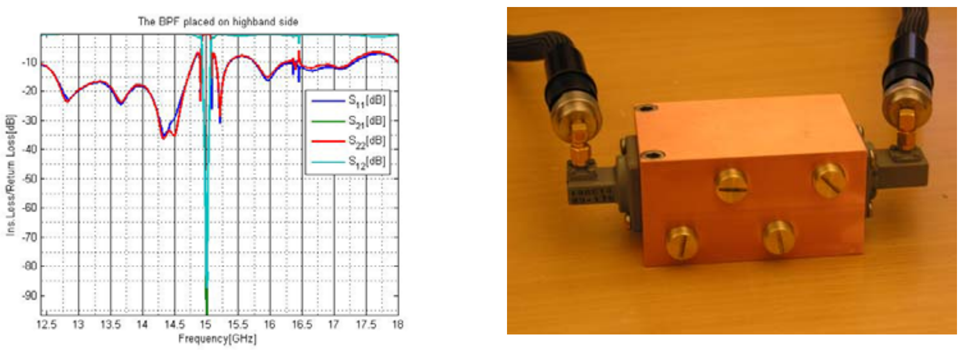

Figure 34. The measured S-parameters of the 4 cavity notch filter and the machined filter realized. The red curve shows the return loss while the green one presents the notch.

2.3.18 Impact of fast ions due to auxiliary heating on the measurement of fusion alphas in ITER

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Collective Thomson scattering (CTS) has been proposed for measuring the phase space distributions of confined fast ion populations in ITER plasmas. Auxiliary heating such as neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH) will accelerate ions in ITER up to energies in the MeV range, i.e. energies which are also typical for alpha particles. Fast ions of any of these populations will elevate the CTS signal for the proposed CTS diagnostic in ITER. It is of interest to determine the contributions of these fast ion populations to the CTS signal for large Doppler shifts of the scattered radiation since conclusions can mostly be drawn for the dominant contributor. In this collaboration between Risø DTU, CEA and TEKES, the impact of fast ions accelerated by ion cyclotron resonance heating (ICRH) and neutral beam injection on the ability of CTS to diagnose fusion alphas in ITER has been determined. For this purpose, distribution functions of fast ions generated by NBI and ICRH are calculated for a steady-state ITER burning plasma equilibrium with the ASCOT and PION codes, respectively. The parameters for the plasma, the auxiliary heating systems, and the CTS system correspond to the design currently foreseen for ITER. For these conditions, synthetic CTS spectra typical for the CTS diagnostic at ITER could be computed. We find that fusion born alphas generally dominate the total CTS signal for large Doppler shifts of the scattered radiation. The exceptions are limited regions in space with some non-negligible signal due to beam ions or fast 3He which give rise to about 30% and 10–20% of the CTS signal, respectively.

2.3.19 Collaboration with the CTS teams at LHD and FTU

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During 2008, contacts to the CTS groups at LHD, NIFS, Japan, and at FTU, Frascati, Italy intensified, and agreements on collaboration were made. The aim of the NIFS CTS team is primarily to perform bulk ion temperature measurements on LHD. A secondary target will be to do measurements of H/D fuelling ratio and of fast ion dynamics. The team will initially use an existing 77 GHz gyrotron, with which they can probe between the fundamental resonance and the second harmonic. The LHD CTS diagnostic was commissioned during the fall 2008 campaign of LHD. During March 2008, the NIFS team invited a Risø DTU CTS team member to facilitate discussions and sharing of experiences on building a CTS diagnostic, and in February 2009 two scientists from NIFS visited the Risø DTU CTS group at TEXTOR and Risø. They were fruitful visits and the collaboration will continue.

The planned CTS project at FTU will expand the knowledge and experience on running a CTS diagnostic with a frequency below the fundamental resonance. A key challenge is that the high power probing beam will cross the fundamental resonance in the transmission line. The solution to this challenge and other issues will be important inputs to the knowledge base, based on which the ITER CTS diagnostic will be designed. The scheduled 2008 experiments on FTU were postponed, and the connection between the Risø DTU and the ENEA teams is still maintained.

2.4 Publications

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Salewski, Mirko; Bindslev, Henrik; Furtula, Vedran; Korsholm, Søren Bang; Leipold, Frank; Lucas, Matthieu; Meo, Fernando; Michelsen, Poul; Nielsen, Stefan Kragh. Heating of First Mirrors for Millimetre Waves in ITER. Presented at: 2nd ITER International Summer School. Fukuoka (JP) , 2008

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3 Fusion Technology

3.1 In-Situ study of coated conductor high temperature superconductors using high energy synchrotron x-ray diffraction

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It has been concluded in the Power Plant Conceptual Study (PPCS) report [1] that the superconducting magnets, which are providing the magnetic confinement of the plasma in a commercial fusion reactor, must become cheaper than the present superconducting technology of the ITER reactor in order to provide a reasonable production price per kWh. It is believed that this can be achieved by increasing the operation temperature from the typical range T = 2-4 K obtained by liquid helium techniques and to the range T = 65-77 K obtained by liquid nitrogen. As a consequence then the confinement magnets must be based on the high temperature superconductors, which are available in the form of wires made of $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi-2223) ceramic in closed in a silver matrix or coated conductors of $RBa_2Cu_3O_7$ (R = Y or Rare Earth) deposited on metal substrates. The Bi-2223 superconductor has a very high anisotropy of the critical current when a magnetic field is applied either along the c-axis or the ab-plane of the crystallographic unit cell and at elevated temperatures T = 65-77 K. The Bi-2223 superconductor will therefore not be able to operate at liquid nitrogen temperatures and in 12-14 Tesla magnetic field, but must be cooled below T = 20 K. Thus the best superconductor candidate is the coated conductor, which has been improved dramatically during the last 5 years, but there is still a need for a reduction of the price and methods suitable for large scale production.

Risø has previously used in-situ high energy synchrotron x-ray diffraction in the optimization of the heat treatment of Bi-2223/Ag tapes [2] and MgB_2/Fe wires [3]. The technique is based on the fact that high energy photons E = 70-100 keV created by a synchrotron can penetrate several mm of material containing heavy elements. Thus it is possible to place a sample inside a furnace with suitable windows and obtain a diffraction pattern of the sample with a time resolution of 1 minute. This is usually obtained in transmission mode where the beam passes through the entire sample and the diffraction pattern is collected on the backside of the sample as shown on Figure 35.

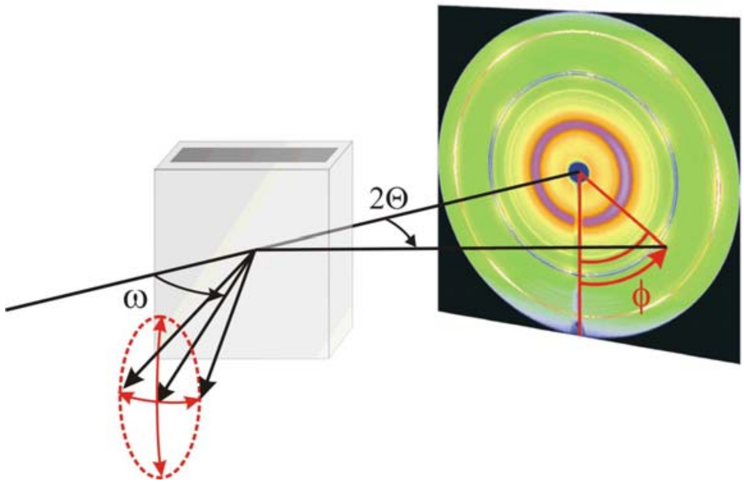

Figure 35. Illustration of setup for in-situ studies of the Mg + 2B → MgB_2 reaction inside an iron tube [3]. A synchrotron photon beam with E = 70-100 keV is send through a monitor and is then illuminating the sample inside a furnace (not shown). Any type of powder grains with crystallographic plane distance d will cause a diffraction cone with a scattering angle 2θ, given by Bragg's law $\lambda = 2d \sin(\theta)$, where λ is the photon wave length. However if the powder is textured with preferred orientation, as shown by the black arrows, then one must rotate the sample in order to get the grains to fulfil the Bragg condition, $\omega = 2\theta/2$.

The metal substrates of coated conductors are either a Ni tape with bi-axially texture obtained by rolling or a Hasteloy tape. A series of ceramic oxide layers are then deposited on top of the metal substrate in order to match the lattice parameter of the top buffer layer with the lattice parameter of the $RBa_2Cu_3O_7$ film. The final superconductor film with bi-axial texture is then obtained and the orientation deviation between the superconductor grains must be below 5 degrees in order to allow the super current to flow between the grains. Thus the heat treatment of coated conductors involves an optimization of each buffer layer and the in-situ technique provides information about the chemical phase purity and the texture of the layers.

We have constructed a new sample stick made completely of ceramic in order to do the in-situ reaction of the superconducting layers of coated conductors up to T = 1000 ^oC and in an oxygen atmosphere (see Figure 36).

The diffraction patterns from several commercial coated conductors have been collected at room temperature by rotating the sample by the angle ω during several exposures of the image plate. Figure 37 is showing an example of a 200 nm thick CeO_2 buffer layer deposited on a 100 μm thick bi-axially textured Ni substrate produced by a water based sol-gel method at Risø-DTU. The pattern is constructed by summing a series of images taken at different ω angles. The texture is determined by the Gaussian FWHM = 3.7 ^{o} of the intensity distribution and shows that the obtained buffer layer is a good template for growing the superconductor film.

An in-situ experiment was performed on a water based Nd:Ba:Cu (1:2:3) sol-gel film on top of a $(LaAlO_3)_{0.3}$ $(Sr_2AlTaO_6)_{0.35}$ single crystal substrate by heating the film to T = 950 ^oC. The sample stick was working perfectly and showed no sign of degradation or lack of holding ability. However the use of a single crystal substrate was causing problems, because the synchrotron beam was not optimized to decrease the higher harmonics of the wiggler. Thus we detected a lot of extra diffraction spots, which were not supposed to appear and we had to limit the exposure time of the detector in order not to burn it. We believe that this problem can be solved by decreasing the synchrotron beam size and work without absorbers. Additionally, we are planning to improve the resolution of the synchrotron setup and thereby further removing the reflections due to the higher harmonics. Finally, all these problems will disappear when the in-situ experiments are performed on real metal substrates as shown on Figure 37 and we are working on obtaining such samples for the next beam time.

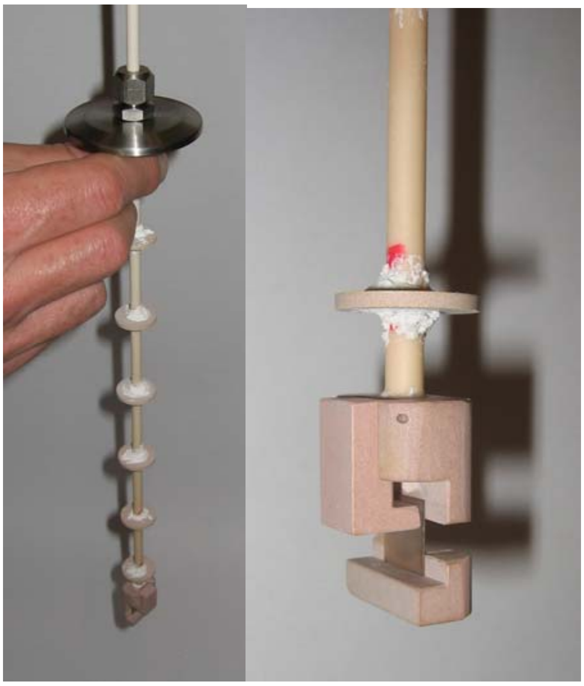

Figure 36. All ceramic sample stick for in-situ studies of the phase formation of coated conductors. **Left:** Sample stick with a metallic top for sealing the reaction gas inside a quartz tube of the furnace. The rings on the ceramic tube serve as radiation shields and the sample holder is sitting at the bottom. **Right:** Close up of the sample holder, where a $SrTiO_3$ single crystal substrate with a Nd:Ba:Cu (1:2:3) sol-gel film deposited on top is mounted at the sample position.

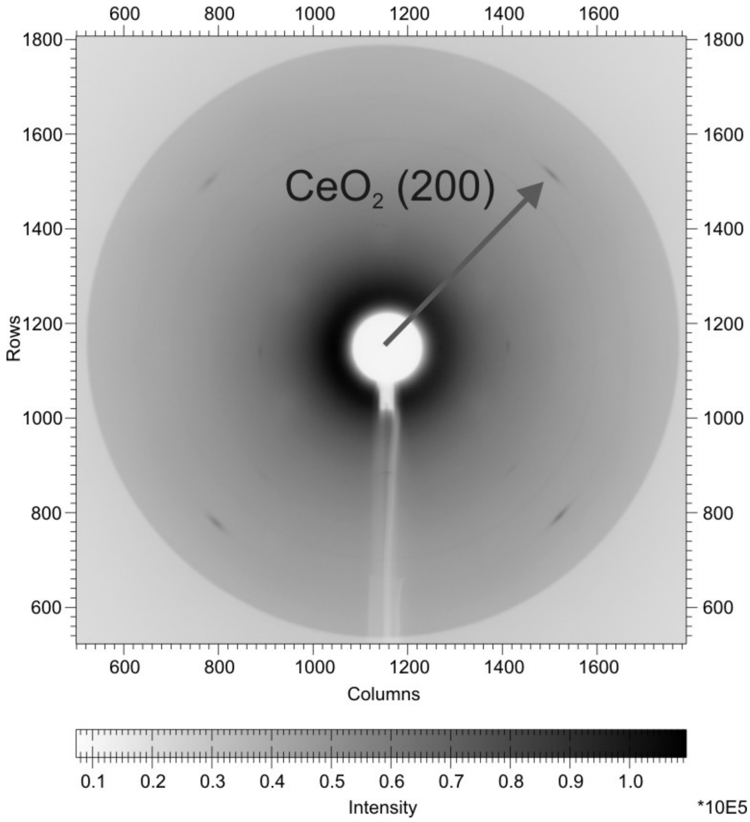

Figure 37. Diffraction pattern of a 200 nm thick CeO_2 buffer layer on top of a 100 µm Ni metal substrate obtained by summing a series of images collected at different rocking angles ω as shown on figure 36. The grain distribution of the ab-plane orientation of the CeO_2 buffer layer is seen from the intensity distribution and a texture of 3.7^o is derived.

1. D. Maisonnier, *et. al.*, ”A conceptual study of commercial fusion fusion power plants”, Report EFDA(05)-27/4.10 (2005).

2. H. F. Poulsen, *et. al.*, “Structural studies of BSCCO/Ag-tapes by high-energy synchrotron X-ray diffraction,” Physica C, vol. 298, p. 265–278 (1998).

3. A.B. Abrahamsen *et. al.*, “Kinetics of MgB_2 phase formation studied by in-situ synchrotron x-ray powder diffraction”, IEEE transaction on applied superconductivity, vol. 17, 2757 (2007).

4 Risø contribution to EFDA-TIMES

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Since the end of 2004 the EFDA and the Associations are developing a multi-region global long-term energy modelling framework called EFDA-TIMES.

The EFDA-TIMES model is a global model divided into 15 regions with the time horizon year 2100. This structure is similar to other global models in TIMES, developed for the International Energy Agency (IEA) and the US Department of Energy. In these models the energy system is divided into the following main sectors: Upstream, Electricity, Industry, Residential, and Transport. Fusion technology is modelled in the

Electricity sector in competition with renewables and electricity generating technologies based on fuels. Risø DTU has contributed to the development of the model during 2007 and 2008 on the upstream sector (fossil resources, refineries, renewable potentials, etc.), emphasising technology learning. Risø was responsible for renewable technologies, in practice biomass technologies. The work on the EFDA-TIMES model is linked to other modelling work using the modelling tools of the IEA Implementing Agreement ETSAP (Energy Technology Systems Analysis Programme) [1].

In 2007 the EFDA Steering Committee initiated the procedure of establishing an Ad-Hoc-Group (AHG) to assess the Socio-Economic Research on Fusion (SERF) programme against the objectives originally stated by the Fusion Programme Evaluation Board in 1996. The AHG finished its assessment of the achievements of 10 years of SERF studies in early 2008 and presented recommendations for revised objectives of the programme, taking into account the evolution of the worldwide context since 1997 (e.g. ITER is now decided, climate change is widely recognised, energy prices are rising). In these recommendations from the AHG the general objectives of the development and exploitation of EFDA-TIMES are

- to develop consistent long-term energy scenarios containing fusion as a sustainable energy option and showing the potential benefits of fusion power as an emission free energy source,
- to gain visibility, credibility and recognition by contributing with these scenarios to the international scientific energy debate,
- to bring the fusion option into other long-term energy models, by making available the latest technical, economic and environmental dataset on future fusion power plants,
- to explore the conditions that make fusion a successful contributor to sustainable energy systems,
- to provide domestic and European decision makers, by making use of EFDA-TIMES, with analyses and arguments in support of the potential benefits of ITER and longer term fusion R&D, and
- to maintain and develop the related know-how in the associations and collaborating university institutes.

Most of the Associates who took part in the previous work on the development of EFDA-TIMES are included in the Task Agreement for “EFDA-TIMES & Fusion Economics” within the work programme 2008 & 2009 (WP08-SER-ETM). Risø DTU will contribute to “Update and validation of assumptions for technologies that will compete with fusion in the future, focussing on biomass and Carbon Capture & Sequestration (CCS)”

1. P.E. Grohnheit, Using the IEA ETSAP modelling tools for Denmark, Risø-R-1656, Risø DTU, December 2008.

5 ITER and Danish industry activities

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Following the ITER site decision on June 28th 2005, Risø DTU was the main driver in the launch of activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER as described in some detail in [1]. This effort originally initiated in 2005 was further developed in 2006 and continued in 2007 and 2008.

In short overview the primary entry gate to the initiative for Danish companies is a website http://iter.risoe.dk. The website contains information on the coming tasks at ITER, background information, news and announcements of workshops etc., links to relevant international websites, description of experiences of other Danish companies, and an online database, where approximately 20 companies present their fusion relevant competences and their interests in ITER tasks. The database includes a number of significant players among Danish industries. It was the original intension that the webpage should also be used to advertise tender actions from ITER and F4E. However, until now it has been found to be more efficient to send out email alerts to the companies.

In parallel to the website, a mailing list of more than 50 company contact persons is maintained. This has been the most important way of distributing news and advertising tender actions. The volume of the list has been steady over the last year with a few newcomers.

A group of companies and research institutes has formed an informal, non-exclusive network (further described in [1]): the Danish ITER Industrial Network. During 2008, one network meeting was held; and while some companies have expressed the wish for further meetings, there have not been sufficient resources from our side (see further below).

In October 2008, Risø DTU accompanied a Danish company to the first thematic CODAC workshop, and in November 2008, Risø DTU and representatives for two Danish companies participated in the first F4E-ILO meeting in Barcelona. Each national ILO was accompanied by up to three company representatives, and it turned out to be an important event for networking.

The earmarked resources for the initiative in 2008 as well as in the future have been and currently are insufficient for the desired volume of the activities at Risø DTU. Furthermore, companies and other research institutes have a wish for support of the extensive preparations for ITER tasks. Therefore, in 2008 a significant effort has been put into a search for appropriate funds. In 2007, funds for a so-called *innovationskonsortium* was sought to be established in collaboration with FORCE Technology and Teknologisk Institut and a number of companies. While this attempt failed, a new and more appropriate possibility emerged in 2008 with the announcement of substantial funds for 4-year *innovationsnetværk* (network of innovation). An application was created in collaboration with FORCE Technology and Danish Technological Institute, and with support from the Confederation of Danish Industry, the Danish Export Council, a regional business growth centre, a regional innovation centre, and a number of Danish companies of different sizes. Unfortunately, this application was rejected.

Despite the unfortunate development described above, contact is still active between the partners in the *innovationsnetværk* while very little concrete effort can be invested i this a present.

The EU ILO network was in 2008 converted into the F4E-ILO network, where the Danish representative still is Søren B. Korsholm, ILO of Association Euratom – Risø DTU. The network now comprises 17 ILOs.

1. Association Euratom - Risø National Laboratory, Technical University of Denmark, Annual Progress Report 2006

6 Public information in Denmark

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The public information activities in the Danish fusion association comprise a broad range of activities from press contact, assisting students to talks about fusion at different venues. A major part of the activities are the further development and the performances of the Fusion and Plasma Roadshow, described below in sections 6.1 and 6.2. A further public information initiative in 2008 has been the fostering of the idea and creation of a Tokamak Trump Card game (by M. Salewski), where the players may compete with tokamak parameters from around the world, after the principle of the well-known Car Trump Cards. A prototype game has been created, but as it is still not in its final incarnation, it will be reported on fully in the annual report of 2009.

For brevity the activities are put in list form below

- More than ten popular lectures on fusion energy – mainly the roadshow at high schools, libraries, cafés, the engineering association, and a fellow university.
- Distribution of fusion material to interested individuals, organisations, and libraries
- Translation and printing of the EFDA Cleaner Energy for the Future brochure
- Translation for Danish subtitles of the EFDA Fusion 2100 movie
- Assisting students from primary and high school in fusion oriented projects
- Contact to journalists (newspapers, radio and TV) on fusion and ITER related news
- Continued participation in the *Scientarium* - the Panel of Experts of Ingeniøren – Engineering Weekly News Magazine
- Maintenance of web pages – also including a site with popular information on fusion (in Danish). http://fusion.risoe.dk and http://fusionenergy.risoe.dk

The EFDA Fusion Educational Poster was translated and printed in 2007 and an application for funds has been submitted with the aim of distributing the poster to all high schools in Denmark. No decision yet.

Generally, about the Public Information effort, it is the impression that interest is rising on the issue of fusion energy – not the least among the high school students.

6.1 The Danish Fusion and Plasma Road Show

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As part of the ongoing public information activities, the Danish Fusion and Plasma Road Show have been created by members of Association Euratom-Risø National Laboratory, Technical University of Denmark, DTU. The show was initiated in 2007 having the Dutch Fusion Road Show from FOM-Institute for Plasma Physics Rijnhuizen as inspiration. The show is funded for three years (2007-09) by the Danish Research Council for Nature and the Universe under the Ministry for Science, Technology and Innovation – by a total of approx. 40,000 Euro.

The target audience of the Fusion and Plasma Road Show is primarily high school students, but has also been shown for a broader audience in public venues e.g. libraries. The show is participating in the Danish National Science Festival (September 2008) and in the National Day of Science (April 2008).

The objective of the show is to inform students and the general public about present fusion energy and plasma research and in that way give them an insight and hopefully an interest in science and its uses. In particular we hope that the students get inspired by the physics and see that fusion energy research is an exciting field with many possibilities. Another important objective is to inform about the use of fusion as a source of energy, and in that way clarify the benefits and challenges of fusion power.

The show is a combination of a regular slide based presentation and a number of small experiments that demonstrate or is related to a topic described in the presentation. The experiments are intended to surprise and excite people and also work as intermezzos in the talk. This is intended to help keep people focused on the topics. In the presentation a great effort is put in simplifying the advanced topics, and it is intended to bring the involved phenomena close to people's experiences from everyday life. This is done e.g. by converting enormous numbers in strange units into meaningful sizes, and also by asking questions or giving small exercises to the audience. The show has its own website: http://roadshow.risoe.dk, where descriptions of the experiments can be found.

In the course of the road show the following experiments are conducted

- Jacob's Ladder: Plasma created by 10.000 V between two copper wires (New in 2008)
- Plasma in a microwave oven: Example of a RF generated plasma
- A ball on a rotating disc/turntable: Ball will move like a charged particle in EM-field
- Smoke rings: Example of the torus shape
- Electromagnet and compasses: Example of electricity generating a magnetic field
- Eddy currents in a copper plate with a strong magnet: Example of the connection between temperature and conductivity
- Superconductor – and example of the superconductor
- Plasma ball lamps

Additional experiments are being developed. Figure 38 holds two photos of some of the roadshow experiments.

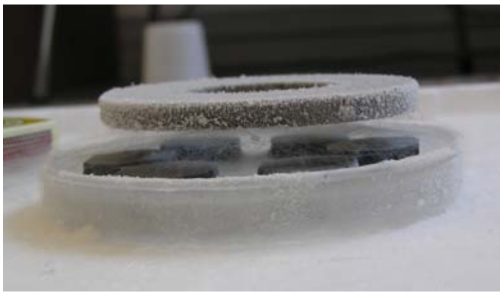

Figure 38. A magnet floating on top of a set of superconductors (left). At the picture to the right the plasma lamp has attracted the attention of two young scientists. Next to the lamp to the left the bottom of the Jacob's Ladder experiment is seen.

In 2008, the roadshow has been performed ten times in Denmark in its regular form. Five of these were at high schools all over Denmark during the national Danish Science Festival in September 2008. At the National Day of Science in April 2008 three road shows were performed as public lectures in cafés and a library, while the road show also participated in a four hour event in Roskilde with an interactive booth. On top of this the road show was booked for the prime time of a science marathon day at the Observatory of Brorfelde, as well as for a youth science association.

The funding for the roadshow will stop by the end of 2009, and we will apply for an extension of the grant.

6.2 The Fusion and Plasma Road Show at the European City of Science

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The Danish Fusion Road Show was asked by EFDA to participate alongside the Fusion Expo at the *European City of Science* event on November 14th to 16th 2008. The event was hosted by the French EU chairmanship in Grand Palais in Paris. The European fusion stand had been allocated stand #1 just in front of the main entrance, through which more than 42,000 visitors passed.

The international team for the EFDA stand consisted of Jean-Marc Ané, Gloria Falchetto (CEA), Fernando Meo, Søren Korsholm, Martin Jessen (Risø DTU) and Örs Benedekfi (EFDA). The road show constituted an important part of the stand, and the impression after the event was very positive with a lot of very interested audiences in all ages and backgrounds. Figure 39 holds two photos of performances in Grand Palais.

Figure 39. Demonstrations of the Fusion Roadshow at the European City of Science, Grand Palais, Paris.

Risø DTU is the National Laboratory for Sustainable Energy. Our research focuses on development of energy technologies and systems with minimal effect on climate, and contributes to innovation, education and policy. Risø has large experimental facilities and interdisciplinary research environments, and includes the national centre for nuclear technologies.

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